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PHYSICS

of the

20TH CENTURY

By
PASCUAL JORDAN

Translated by
ELEANOR OSHRY



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PREFACE

This book tries to present the concepts of modern physics in a systematic, complete review. The reader will be burdened as little with details of experimental techniques as with mathematical formulations of theory. Without becoming too deeply absorbed in the many, noteworthy details, we shall direct our attention toward the decisive facts and views, toward the guiding viewpoints of research and toward the enlistment of the spirit, which gives modern physics its particular philosophical character, and which made the achievement of its revolutionary perception possible. First, we shall review the classical Galilean-Newtonian mechanics. A thorough appreciation of this is prerequisite to any understanding of the revolutionary developments of modern physics. Through the development of Maxwellian Electrodynamics we shall arrive at the modern views both in macrophysics and microphysics of atoms, electrons and quanta.

That modern physical research led to revolutionary changes in the traditional concepts of the natural sciences is by no means a new idea. The provocative appeal of these wonderful developments was not the only reason I felt it desirable to write this book. I was anxious, also, to aid in the gradual removal of misunderstandings of the newest developments in physics displayed by many laymen. Continuation of such misconceptions can

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lead to disturbing confusion. Thus, in the public mind, entire chains of misunderstandings have arisen through a fallacious combination of objective scientific questions with wholly different, e.g., purely personal ones. Even after the correction of the gross errors many doubts and obscurities still remain.

Laymen have frequently regarded as a sign of doubt and confusion the fact that even the fundamentals of the previous scientific world-picture have become limited in their validity; that concepts such as space, time, causality have become subject to incisive revisions. They maintained that the new basic fundamentals suggested vacillations, that a threatening crisis had broken out or that unrestrained dogmatism and uncertainty had spread. The newly disclosed phenomena liberated us from outmoded, traditional concepts, thought processes and ideas. This liberation is only a necessary prerequisite for the tremendous growth of our knowledge and understanding which has already begun. The certainty and permanence of our physical science lies in the experimental facts. Here there is no renunciation and reformulation of things already established. Here there is only progressive development of new ideas. The concepts and mental pictures to which we made the facts of the narrower, previously explored domain conform, can be proven insufficient by the broadening of our factual knowledge. Our most wonderful moments of scientific evolution are experienced when it is shown that we must revise our ideas from the ground up to agree with a new con-

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cept. Modern physics effected many such changes; and in the most fundamental respects. That is what this book would like to tell about.

When, in the preceding paragraph, we summarized what these developments yielded in principled, philosophical information, it seemed natural that from our newly gained position we would undertake a reexamination of the picture of the physical world as well as of the meaning of non-physical questions.

Certainly the religious question cannot be avoided here. Bavink, in a very noteworthy way, attempted by means of the insight of the new physics to present a new answer to the old problem of the relation of natural science and religion; it seemed worthwhile to me to further investigate the relation of the scientific theoretical philosophical standard being expressed in modern physics to Bavink's ideas.

It was inevitable that the author's personal judgement should assume some weight in the choice of facts and questions discussed, in the discrimination between important and unimportant concepts, in many an outline of a reported development of ideas, and in the philosophical evaluation of methods of reasoning and results.

It was my endeavor, however, to limit the description as strictly as possible to things which were scientifically proven and independent of personal opinion; thus to include only proven experimental facts reported by leading, authoritative investigators whose opinions are a reliable basis for drawing conclusions and knowledge.

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This strict limitation forced me to cease consideration at the point where it led to questions outside of the boundaries of physics—questions encountered and placed in a new light because of the revolutionary change of our physical conception of the world. In three points especially this necessity applies:

1. In the investigation of the relation of modern physical research to the religious question any positive conclusion about religious possibilities must be supplemented by an acceptance of the possibility of the validity of the former anti-religious position of science. The reader will not be able to recognize whether the author personally inclines toward an historically old or a modern idea of religion—although actually, the author has a very definite personal opinion on this subject.

2. Likewise, it would be overstepping the above designated bounds to discuss the question of the deeper, spiritual relationship between the revolution in physical thought and knowledge described in this book and the far-reaching changes which are taking place in the whole world outside of science. To me, modern physics and its accompanying revolution in century old conceptions of physical science is an integral component of the unfolding of the new world of the twentieth century.

3. Finally, it seemed worthwhile to include just a short reference to an important field of thought which really belongs within the realm of pure science, but not strictly within the boundaries of physics. This is the problem which has been

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raised in biology by the changes and the extension of our physical knowledge. Despite the skepticism with which my ideas on this subject (in another book) were appraised by many biologists, one of the most important biological theses which I indicated as probable has just recently been verified experimentally: Timoféef-Ressovsky, Zimmer and Delbrück showed that genes are molecules and that mutations are elementary quantum-physical processes. The wonderful insight almost simultaneously arrived at that virus individuals, like genes, are nothing but single molecules (Stanley), strengthened the proof of my biological-atomic physical theory. On the basis of the extensive experimental material, which was compiled through the investigation of the biological effects of radiation, I could briefly prove the general usefulness of an atomic-physical and quantum-physical interpretation of the elementary life processes (in the sense of my "Theory of the Increase of Organisms"). But a presentation of this matter would be going too far beyond the framework of this book.

Just a third of our century of physical research, opened by Planck's discovery of quanta (1900), has elapsed and physics presses forward at a tempestuous rate toward new discoveries and conquests. It may therefore appear presumptuous to speak already of a "Physics of the Twentieth Century". But two things appear to me to leave no room for doubt: first, that the consummated revolution of our scientific knowledge is not to be made retrogressive by future new discoveries. And secondly, no matter how

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far beyond present attainments the future decades lead, the discovery of Planck's quantum of action must in the future also remain recognized as the historical breaking point at which the epoch of scientific research which began with the Renaissance ended, and a new epoch was opened.

—P. J.

CHAPTER I

CLASSICAL MECHANICS

1. *Macrophysics and Microphysics.* Modern physics accepts the atomic structure of matter. Matter, palpable and visible to us, is made up of large numbers of minute bodies, called atoms, which can neither be seen nor felt. Greek philosophers had suspected the existence of atoms, and this concept taken over from the Greeks has played an important part in scientific investigation and development since the beginning of western scientific research. But it was not until this century that what had been supposition, speculation or fantasy was raised to the rank of solidly established scientific knowledge confirmed by direct experimental proof. It can even be said that ours is the century of atomic research in physics; and a survey of the ideas of modern physics should first of all deal with the investigation of atoms.

But the first two chapters deal with those fields of physics which do not involve any discussion of atoms. For the moment, let us consider a piece of homogeneous matter capable of being subdivided. A piece of copper or a piece of rock crystal can be broken and split up into smaller and smaller pieces, and the fragments continue to show the characteristic properties of the copper or the quartz. Even if certain limits existed for the practical accomplishment of such a subdivision—it is difficult to break up into smaller parts quartz which has already

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been ground up to dust—yet this rough experiment presents no criterion for the existence of a definite, clear limit to further subdivision. The dust particles still differ in size and shape among themselves. Thus one might conclude, that—even though our tools are ineffective—nature presents no obstacle to halving the smallest dust particle once more, and to halving this half again, and so on... without a limit.

Today we know with certainty that that is false. But very refined methods are required to attain the limit to the continued division of matter—in other words, for the experimental determination of the atomic structure of matter. But, as previously stated, such methods have been available for only a few years. Thus there are large and rich fields of physical research in which the atomic structure of matter is not at all recognizable. Naturally no information about atoms can be expected from such research, but then no knowledge of atoms is necessary, as long as investigation is limited to these fields. It is customary to speak of macroscopic physics (or macrophysics) when referring to those investigations in which the presence of atoms is not discernible; on the other hand research which penetrates into the atomic detail of matter is denoted as microphysics.

This review is devoted in large part to a discussion of microphysics—but since only a thorough comprehension of macrophysics can make possible an understanding of microphysics, we shall begin with a discussion of the former. Moreover, it was in our century that macrophysics reached its final ma-

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turity, and therefore several of its chapters also form an extremely modern science. It was in these recent developments that certain philosophical theoretical thought processes were developed and clarified, making it possible to reconcile the surprising and paradoxical results of microphysical experiments, which previously were difficult to understand.

We are beginning with very simple things. Despite their simplicity, however, they merit careful and thoughtful consideration.

2. *The Laws of Falling Bodies.* The Greeks had already established the laws of statics, of mechanical equilibrium of levers and of fluids. The essentials of these laws had been clarified. On the other hand, dynamics, the theory of the mechanical laws of motion, was first established by Galileo. It is not within the province of this review to trace the historical development of Galileo's investigations; although for a deeper spiritual historical understanding of modern science, closer consideration of the historical origin of modern physical thought—up to the end of the Middle Ages—would be very valuable. We shall simply consider Galileo's laws of falling bodies in their finished form. The simplicity of these laws and the ease with which they can be interpreted today should not deceive us as to how tremendous was his mental capacity. To judge his contributions fairly, the historical-cultural background and the ideas—so completely changed and readjusted since then—prevalent in pre-Galilean times should be considered.

Let us consider the motion of a falling or pro-

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jected body. Simple, everyday experience indicates that a feather falls more slowly than a piece of lead; and Aristotle had taught generally that light bodies fall more slowly than heavy ones. Galileo's main contribution is that he recognized the possibility of extracting an obscure but simple law from the amazingly complicated motions of real projected bodies; he considered falling motion in a vacuum. It is possible to prove that in an evacuated tube a feather falls as quickly as a piece of lead—this experiment is part of the course of study in schools today. But Galileo's contemporaries still considered the idea of a vacuum as impossible, as nonsense. In those times it required far greater strength of intellectual abstraction than we might expect today, to recognize that it was possible to separate (mentally) all the associated events from the motion of falling bodies. We know today that the effects which originate from atmospheric pressure and the influence of the wind can lead the motion of a falling feather to proceed entirely differently from that of a falling stone.

But it is possible to extract from all these complex and varied motions an ideal form which is to be regarded as the motion of a body in a vacuum. This "ideal" projectile motion is wonderfully simple compared to the actual motions of falling bodies or projectiles:

1. Ideal projectile motion is always a plane motion (proceeding within a fixed plane perpendicular to the earth's surface).
2. It proceeds independently of the mass, size and shape of the projected body; it simply

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depends upon the magnitude and direction of the initial velocity.

3. It is not influenced by any rotation of the projectile around its own center of gravity; even if the body rotates around it, this center of gravity moves according to the law of ideal projectile motion.

These properties do not properly describe the motion of a real bullet, which is not exactly a plane motion, and which depends very substantially on the mass, size and shape of the projectile as well as on its spin (rotation).

Here we witness one of the historically most important examples of physical natural scientific thought. The phenomena presented to us directly by nature are so varied and complex that it is impossible for our narrow minds to grasp them individually. We must mentally divide these natural occurrences into their simpler components; we must consider results of artificially produced extremely unnatural conditions instead of those offered through direct experience. Thus we uncover the ideal cases, which can be subjected to more precise, considered treatment. These results in turn establish criteria for the evaluation of the real events, in each case different from the ideal to a greater or lesser extent.

Now let us consider the laws of ideal projectiles more exactly. For this we want to view the simplest case, namely vertical rectilinear fall. The body, first retained at rest and then released, falls downwards—as long as it continues to fall—with ever increasing velocity. At the instant of release, the velocity is exactly zero, but thereafter it increases

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steadily. This increase does not proceed in intermittent, rapidly repeating, sudden jumps, but rather in an uninterrupted, continued growth, in which there are neither pauses nor sudden discontinuities. Mathematicians express it very clearly when they say that the velocity increases uniformly.

In such a case, when the velocity is changing uniformly and constantly so that it is never the same at two different points in time, no matter how closely they may follow one another, what does velocity mean?

When a body moves with uniform velocity it is clear what velocity means—the distance traversed is divided by the time of travel. We commonly say that a body traveled at a velocity of one meter per second or that an auto traveled at seventy kilometers per hour. But how are we to understand and define velocity abstractly if it doesn't remain fixed throughout even a fraction of a second?

In Galileo's times this question presented very great difficulty; the abstract and mathematical tools for solving it were still lacking. In an evaluation of Galileo's contributions, this fact, too, must be remembered. Galileo had been able to dispose of these questions completely for ideal projectile motion; it only became evident later how great an achievement this was. Newton cleared up the concept of velocity (and acceleration) quite generally, for any motions. For this purpose he had to establish an entirely new branch of mathematics, the so-called differential calculus.

Differential calculus (including the chapters of mathematics connected with it) is undoubtedly the

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greatest creation achieved by western mathematicians. In this Leibnitz stands beside Newton as the founder—although his considerations did not emanate from mechanics, but rather from geometry. Naturally both of them, Leibnitz and Newton, referred back to forerunners and trailblazers; in the problems of their time and in their natural scientific and mathematical investigation there lay an inevitable compulsion toward this direction of thought. But what they produced by bold statements occupied generations of mathematicians after them and stimulated further great results.

This new mathematics, which is an original creation of western thought, not anticipated by the Greeks, deals with precisely those questions which confront us when we inquire about the exact meaning of the “concept” of velocity in the case of constantly changing velocity. The function of differential calculus is to express clearly mathematically quantities that describe constant, fluid, continuous change. For this reason the idea of continuity is the central, controlling concept, around which the thought paths of this chapter of mathematics revolve.

The exact definition of velocity can be expressed as follows. First, it is clear what is meant by the average velocity within a given time interval—the distance traveled in this time is divided by the length of time. Now, in order to obtain the exact velocity for a given point in time we choose a small time interval (including this point in time) and determine the average velocity associated with this interval; it will, if the time interval chosen is small

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enough, give an approximately correct value for the exact velocity desired. This value can be improved by replacing the time interval with one half as large; and then this improvement can be repeated. It is frequently possible to repeat it mentally at pleasure, and thus with unlimited approximations to approach ever more exactly the precise value desired.

This, therefore, is the definition of the concept of "velocity". The problem is no simpler if one wants to obtain the results quantitatively, and for this purpose wants to sharpen the concept so that it will make a mathematical evaluation possible—when one does not want to be content with a solely emotional, indefinite application of the concept. But one need not fear that this has led to a hopeless, practically insoluble problem in calculation. On the contrary, there are ingenious considerations (and their cultivation is the inherent content of differential calculus) which make it possible to establish in a specific form of motion the limiting value which we must take as the basis for the definition of velocity.

Galileo had already answered these questions for ideal falling motion. He had recognized that for this ideal motion, dissociated from air resistance and all secondary influences, a wonderfully simple law exists; namely, velocity increases proportionally with time. Thus, after double, triple, etc., time of fall it is exactly doubled, tripled, etc.

This law extends also to general ideal projectile motion. If we throw a body vertically upwards or downwards, its downward velocity will still always increase in proportion to time—which in the

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case of upward motion naturally means a corresponding decrease in the upward velocity. If it is thrown obliquely, the body's height measured vertically to the earth's surface (in ideal projectile motion) changes with the passage of time exactly as if it also were a vertical fall. Simultaneously, the horizontal distance from the starting point increases proportionally with time; or expressed differently, in the horizontal direction the motion proceeds with fixed velocity. Mathematical consideration of these determinations yields the fact that the projectile path (trajectory) is a parabola.

3. *Force and Motion.* The laws of generalized ideal projectile motion formed another example of how scientific thought made natural processes comprehensible through resolution into simpler components. We conceive of parabolic motion as simultaneous execution of two different motions, vertical and horizontal. It is also possible to study the horizontal motion isolated from the vertical—for this all we need is a horizontal rail, or perhaps a plane ice surface, on which the body can slide. Then for the ideal limiting case (i.e., in the case of not only the absence of air resistance, but also of any friction accompanying the sliding) we reach the conclusion that the body moves in the horizontal direction with constant velocity.

Galileo accepted the certainty of the spherical shape of the earth, at that time not a very old concept; and he could represent the earth as moving freely through space on the basis of the Copernican theory which he accepted. Thus he knew that the motions horizontal and vertical or above and below are only

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relative. And from this the possibility of generally recognizing the basic form of motion, free from external influences, in the ideal, resistance-free motion of a horizontally sliding body became evident. Newton, the first one to state this clearly, expressed his famous law of inertia as follows: a body moving in a vacuum unobstructed and free from external forces moves in a straight line with constant velocity.

Falling motion must thus be conceived as a deviation from the invariable behavior of a body, for which the cause is to be sought in an attractive force emanating from the earth. Newton clarified for all cases the manner in which a force acting on its center of gravity alters the motion of a body—the force manifests itself in a change of velocity, an acceleration. In vertical free fall the acceleration is constant—whereby we define acceleration as the increase in velocity divided by the duration of the fall. For complex motion, in which the acceleration is no longer constant but is subjected to continuous changes the same considerations are necessary as were introduced for the concept of velocity. Newton's new mathematics, differential calculus, mastered all these problems with one stroke.

If we limit ourselves to rectilinear, uni-dimensional motion, then according to Newton the acceleration is exactly equal to the force divided by the mass of the accelerated body. It depends on neither size nor shape, nor material, color nor temperature of the body, but on its mass alone.

The laws of three-dimensional motion are analogously simple and general. Here it is simply neces-

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sary to resolve the motion into three components, acting in mutually perpendicular directions, whose simultaneous execution yields the total effective motion. If the force acting on the body's center of gravity is resolved correspondingly, the above Newtonian law is valid for each of the three uni-dimensional portions of the whole process.

This knowledge made possible a clear definition of the concept of physical causality. The general notion that nothing happens unless a definite cause exists for it was elevated to a quantitative law: a definite force acting on a body imparts a definite acceleration to that body.

This point merits further consideration. To really understand the significance and importance of the ideas which constitute physics, we must always be ready to refer back to previous concepts. Only in this way can we realize how revolutionary such thoughts were at one time, although they have become quite familiar and conversant to us.

As the most prominent feature of natural-physical research we recognize the search for quantitative, mathematically comprehensible laws. We must remember that extreme idealization of natural events is necessary to render this search successful. Since, by eliminating air resistance, Galileo attained the process of ideal fall, he was able to uncover mathematically simple, beautiful, exact laws; and conversely, these laws show that he looked for the idealization in the proper direction.

Naturally calculations on the projectile trajectories of modern weapons do not yield these ideal projection laws at all. Such calculations require

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consideration of air resistance—which also is introduced in a more or less idealized form. Ballistics, which deals with these problems, is a special, highly developed science whose outstanding practical significance needs no special emphasis. But the science of ballistics had nothing new to add for the general development of physical science, for the development of physical thinking and ideas.

The idea of continuity, which attained its mathematical form in differential calculus, is important for the clear understanding of motive processes. We also want to make it clear immediately that this continuity of natural events—"natura non facit saltus"—was already evident in the elementary fact that it was at all possible to speak of a definite trajectory of a moving body. A body cannot reach one place from another by jerks, suddenly disappearing here and emerging again there; it must describe a continuous connected path between the two. But why is that necessary? We know from experience that it always is that way, but is there a logical necessity that it cannot be otherwise? These questions are not idly posed: we shall never be able to understand microphysics unless we have carefully examined such questions.

If we continue to consider macrophysics, it must be realized that in this sphere the principle of continuity is valid without exception. When a shell explodes, the proposition holds that individual fragments can only change their positions through continuous motion, rapid as it may be. Or in an automobile accident—the law obtains that each body can only change its velocity continuously,

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never with "discontinuous", complete suddenness.

Also, the quantitative, mathematical definition of mechanical causality, in which Galileo's and Newton's knowledge culminated, is inseparably bound up with the concept of continuity. For, it is through Newton's law—"force equals mass times acceleration"—that constant changes in velocity are traced back to the forces which cause them.

4. *Relative Motion.* The knowledge expressed in the law of inertia and in Newton's definition of the operation of force was diametrically opposed to earlier views. Previously the problem had been viewed just in reverse—explanations were being sought for the fact that a hurled stone retains its velocity after being released from the hand. It was considered natural and understandable that it must lose its velocity if the impulse is lacking to maintain it. For everyday experience does indicate that a wagon, for example, which is supposed to move uniformly along a straight path, does require a continuous uniform force from the beast drawing it.

The now recognized fact that, exactly opposite, an uninfluenced body retains its velocity without any change—the wagon on the road is not a valid example of this because it is retarded by the action of friction—and that quite generally only acceleration, and not velocity, is determined directly by the acting force, is related to certain very significant problems, which were not fully solved until this century. For the moment these problems are pertinent only so far as they refer to the mechanics of Galileo and Newton.

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Opponents of the Copernican theory of the motion of the earth around the sun had introduced the following objection: if a gun is shot vertically upward, the shot falls down close to the gun. But, they said, according to Copernicus, since the earth has in the meantime moved along some distance, the shot should have fallen down in an entirely different place. This was impressively demonstrated in an experiment by Gassendi: he dropped a stone from the tip of the mast of a rapidly traveling boat. It fell down below near the mast, not on the stern of the boat nor behind the boat in the water.

Galilean-Newtonian mechanics explained this result without more ado. And, since generally it predicted suitable results for all analogous experiments, it lent an indispensable contribution to the justification of the Copernican theory. To our present thoughts, which accept the ideas of Galileo, Newton and their associated mechanics as a basis, the process is clear immediately: the stone, first held in place at the tip of the mast and then released, received the same velocity in the horizontal direction as the boat; and it retained this horizontal velocity (as long as the effect of air resistance was negligible) so that as it fell downwards it moved along with the ship in the horizontal direction.

From the Newtonian laws of mechanics it is obvious that if a boat (or train) is traveling in a straight line with constant velocity, one cannot determine on the inside of a closed cabin of the ship whether or how fast the boat (train) is traveling. Although naturally it can be deduced from the

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altered rocking of the boat or swaying of the train, here we are considering the ideal case of a vehicle moving along smoothly without rocking or bumping.

An object dropped in the cabin will fall vertically to the floor, precisely as it obeys the law of falling bodies on land. Now let us consider that an observer standing on shore can see inside of the cabin. The author desires to establish that the falling object is still subject to the laws of falling bodies, although this observer would not see it fall vertically, but in a parabola—with a horizontal velocity (as long as the effect of air resistance was that of the boat).

The concept of velocity is relative. The observer on shore views all objects in the cabin with a different velocity than the experimenting traveler; for the witness on land every object moving in the cabin acquires in its motion also the additional velocity of the vessel. Therefore, to avoid misunderstanding we must always append to the word velocity “relative to the boat” or “relative to land”.

When a boat travels with constant velocity (relative to shore) then the acceleration of any body relative to the ship is always the same as it is relative to land despite the difference between the relative velocities. Consequently the same mechanical laws apply to motion relative to the boat and relative to land. In both reference systems the same accelerations are caused by the forces acting.

This discovery, that one can never determine uniform motion of a closed room from its inside with any mechanical apparatus—be it simple or complex—whose method of operation is subject to

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Newton's laws, is called the principle of relativity. The principle of relativity is, beside the principle of the conservation of energy, the most general and most comprehensive physical law that we know. As yet we have only established its validity with respect to the laws of Galilean-Newtonian mechanics. But we shall see that its significance extends far beyond this and embraces all fields of physics.

Therefore we can't perceive through any mechanical experiments conducted on the earth that the earth (relative to the sun) glides along thirty kilometers per second, or that the sun (relative to the milky way system) flies along with still greater velocity. And we can't distinguish whether the milky way, which despite its tremendous size is only a small island in space, for its part executes as a unit any uniform rectilinear motion. The rotation of a body, for example, can be recognized by means of mechanical effects. Anyone sitting on a carousel can tell, even with his eyes closed, that it is turning from the centrifugal force which presses his body against the outer wall — since according to the law of inertia the body would fly out in a tangential direction due to the rotary motion if the outer wall didn't retain it. In the same way we notice a curve within a train; we also notice the acceleration or deceleration of rectilinear motion when starting or stopping. It is only uniform progression which is not noticed, because only there is the acceleration of the body relative to the vehicle the same as that relative to the fixed rails.

In the case of our earth the centrifugal force caused by its rotation is evidenced in the flattening

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of the poles. It is also possible to measure the earth's rotation directly through a simple mechanical experiment—whereby the Copernican conception of motion in our solar system, developed from astronomical knowledge, was shown to be a necessary result of Newtonian mechanics. This is the famous Foucault pendulum experiment. A weight swinging on a very long thread transferred into an elliptical form of vibration under the influence of the earth's rotation. The measurement of this effect permits the determination, based on Newtonian mechanics, that the earth actually rotates with the same speed that the "fixed star" sky seems to move (oppositely directed); that actually the "fixed star" sky, as Copernicus taught, remains at rest.

5. *Newton's Law of Gravitation.* The most significant addition that Newton made to Galileo's knowledge was his teaching that the motions of the planets, conceived in the Copernican sense, were to be considered as consequences of the same mechanical laws which were derived from terrestrial falling motion. Newton availed himself of the opportunity to demonstrate conclusively his extension of Galileo's ideas, using as an example the most wonderful mechanical system provided by nature. To his admiring contemporaries the explanation of known processes made possible by the new mechanical principles was convincing proof of the validity and profundity of these principles. It was not exaggeration when H. Poincaré once said that mankind had learned mechanics from celestial and planetary motions.

To his general mechanical laws, valid for all

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effects of mechanical force, Newton added the law of gravitation: any two bodies exert an attractive force on each other that is proportional to the product of the two masses (thus, is doubled, tripled . . . with the doubling, tripling . . . of either mass), and that becomes weaker as the separation between the two bodies is increased. The decrease in attractive force with distance is such that, e.g., the attractive force of the sun on a meteoric stone in interstellar space decreases with increasing separation from the sun in the same manner as the strength of the light emanating from the sun, which becomes increasingly thinned out with increasing separation. Mathematically expressed, the force of gravitation varies inversely as the square of the distance.¹

Newton, by mathematical reasoning, showed that the laws of the motions of the planets (discovered by Kepler) are a necessary result of the gravitational attraction between the sun and the planets. The Keplerian laws state:

1. The orbit of each planet is an ellipse with the sun at one of its foci.
2. Each planet revolves so that a line joining it to the sun sweeps over equal areas in equal intervals of time—so that when the planet is closer to the sun it moves more rapidly than when it is at a more distant point in its orbit.
3. The squares of the periods of any two plan-

¹ This illustration, comparing the mathematical law of the force of gravitation with light, should not be construed to mean that a closer connection exists between these two phenomena.

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ets are in the same proportion as the cubes of their mean distance from the sun.

It is obvious that Kepler's laws differ in nature from the mechanical laws which formed the basis for their final mathematical proof. Actually, Kepler himself viewed his laws in a manner different from Newton's. For Kepler, his laws were primarily an expression of the beauty and harmony of the divine creation; whereas Newton's laws demonstrated in the planetary system the principle of causality in nature, according to which the resultant motions proceed necessarily from the acting forces.

This same gravitational force which regulates planetary motions also determines the orbit of our moon around the earth, or of her moons around Jupiter. This same force which controls the solar system with its planets, comets and moons is also responsible for the fall of bodies on the earth.

In 1666 Newton had already visualized this comprehensive picture of the validity of his law of gravitation. But the calculations did not agree with observations. The magnitude of the earth's attraction working on the moon calculated from the motion of the moon did not appear to correspond in the sense of the Newtonian law with the magnitude of the force of gravity at the earth's surface. Newton concluded therefore, that still other forces come into play here; and unsatisfied, he set this investigation aside.

Not until sixteen years later, when he learned that new geodetic measurements of the circumference of the terrestrial globe had yielded a value

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about one-sixth greater than had been accepted until then, did he resume this work. Now Newton's calculations agreed with observations. Four years later, in 1686, his great work "Philosophiæ Naturalis Principia Mathematica" appeared. In it he developed the principles of mechanics, set up the law of gravitation and taught the mechanics of the planetary systems to be understood on these bases; he also explained the phenomena of the tides.

Shells from modern guns that shoot beyond 100 kilometers have projectile paths whose calculation must include the consideration that the earth is not flat, but is a sphere. Technology thus began to bridge the wide chasm which was opened by Newton's boldness of mind when he recognized that the motions of the moon around the earth and the planets around the sun are dependent upon the same laws as projectile motion on the earth's surface. Newton bridged this gap in the following hypothetical experiment: a projectile is shot off from a high mountain—somewhat horizontally. The experiment is performed repeatedly, with ever increased projectile velocity. The projectile strikes ground farther and farther away; when the velocity is sufficient, at the other side of the earth; and with still greater velocity the case is reached wherein the projectile, by flying around the earth, again reaches the point from which it was shot off. In the "ideal" case of absence of air resistance—which condition actually prevails in interstellar space where the planets move around—the projectile will have maintained its initial velocity; consequently it will describe the same path again; and con-

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tinuing, it will circle the earth permanently.

A characteristic feature of physical research can be detected in this Newtonian extension to planetary mechanics of Galileo's investigation of projectile motion. After obtaining a sure footing in a limited field an attempt is made to transcend the existing boundaries with the conceptions gained in the immediate field serving as a basis for the investigation of the more remote.

By trying to find connection and similarity between the newer phenomena and those previously investigated, an extension and generalization of ideas and recognized laws can be reached. Such generalized laws make it possible to "understand" the entire, extended sphere of experience.

We have just placed the word "understand" in quotation marks in order to emphasize the importance and profundity of the problem of being clear about what is really meant by "understanding" physical events—and what goal is really striven towards in physical investigation and search for knowledge. Newton's celestial mechanics—probably on the whole the greatest contribution of physical thinking ever accomplished—indicated clearly that "understanding" means nothing else than tracing back the new to the already known. Aristotle's question, why a body that has been set in motion retains its velocity, was not answered, but simply brushed aside. The law of inertia establishes that a body invariably and indefinitely retains its velocity as long as retarding forces do not act upon it. And once one is satisfied with this establishment—that is not to be "understood", but simply accepted

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—one also sees the problem of planetary motion from an entirely new angle. One need no longer (as Kepler still desired) assume in the sun the seat of permanent impulsion of planetary motion.

One other point merits our attention before we leave Newtonian mechanics for new subjects. What are the results of the planets' mutual attraction for one another? The mathematical solution of this problem is extremely involved and difficult (the famous "three body" problem). One fact is clear—since the sun's mass is tremendously large in comparison with the masses of the planets, the attractive forces exerted on each planet by the other ones are very weak in comparison with the attraction of the sun. Thus it is understandable that the Keplerian elliptical paths actually do prevail, with only small deviations, weak "perturbations", caused by the mutual effects of the planets on each other.

But shouldn't it be expected that these small disturbances could grow with the passing of time—in such a way that they might change the magnitude and positions of the elliptical orbits completely in the course of millions of years, and the planets would finally have to collide or plunge into the sun?

Newton entertained this suspicion. And he believed that from time to time the world creator must intervene to prevent such destruction. Therefore it was of great significance for the internal consolidation of the natural physical conception that Lagrange and Laplace later showed by clever mathematical proofs that the planetary system possesses "stability" of itself on the basis of the Newtonian law. Therewith the idea was accepted that

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the paths of all events in the universe are controlled in their entire sequence without exception by the mathematically defined natural laws of physics.

CHAPTER II

MODERN ELECTRODYNAMICS

1. *“Action at a distance” and “field of force”.* Newton’s analysis of planetary motions had verified the existence of a gravitational attraction which varies inversely with the square of the distance. The presence of this force could be deduced from Kepler’s laws, from the motions of the moon and terrestrial projectiles, and from the mutual perturbations of the planets, which were subjected to detailed investigations by later astronomers and mathematicians. But a further problem remained—the problem of whether a deeper insight into the phenomena of gravitational attraction could be achieved; the problem of somehow understanding and deriving this attraction of gravity from more basic causes.

The fact that Newton had left this question open led many important physicists of his time—notably Huyghens—to mistrust the entire Newtonian thought structure. Without a deeper, more exhaustive explanation Huyghens refused to recognize Newton’s formulation of the law of attraction as satisfactory. At the other extreme, Newton’s admirers accepted the law of gravitational attraction as a final, independent world law that required no further explanation. With this attitude they did not, however, express Newton’s own feeling; for he had never fundamentally denied the justification of the demands for a firmer establish-

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ment of his law. However, he did state emphatically that he would be content with the determination of the presence of this gravitational attraction and the mathematical law for its quantitative description. With this statement he ceased speculating about its origins — “Hypotheses non fingo”. The problem of the cause of the force of gravity, which despite this remained an open problem for a long time, could not lead any further at that time. But a step ahead was possible with regard to a similar physical law. Coulomb had shown that for attractions and repulsions of electrical charges the force is also inversely proportional to the square of the distance of the mutually interacting charges. Although here, in contrast to the attraction of gravity, a known difference exists—i.e., there are two kinds of electricity, positive and negative, wherein those of similar sign repel and opposites attract—yet, the mathematical law Newton discovered in the attraction of gravity also holds for decrease of force with increasing distance. Physicists of the last century succeeded in obtaining a deeper understanding of these electrical force effects.

How can it be demonstrated that two electrical charges exert forces on each other no matter how far apart they may be? This “action at a distance”, this influence of one physical system on another regardless of the distance between them appeared unnatural to the physical intuition of the investigator. The feeling that such a distant effect could not be basic, but required an explanation and a correlation with fundamentals doubtlessly resulted

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from the influence of materialistic philosophy in the course of historical development; its profound effect on the thought development of western natural science is an unmistakable historical fact. Materialistic philosophy, which taught that atoms of matter, hypothetically introduced by it, were the only seat of action, indicated that the reciprocal effect of atoms through pressure and collision was the only action properly explaining natural phenomena.

Thus it was necessary to explain the apparently independent effects, widely separated from each other, which are stated in Newton's and Coulomb's laws, as results which somehow depended only on pressure and collision of atoms.

Independently of these considerations, which today retain only historical significance, the acute instinct of some investigators of the last century led to the conviction that "action at a distance" must be reduced to a "field of force" effect; that the effects of a physical system could not extend unaided over great distances; that each physical effect must extend continuously in space from place to place.

These convictions were firmly established by Faraday and Maxwell. Faraday, the experimental physicist, allowed his research to be governed by original, new conceptions which in the course of his wonderfully rich experimental discoveries underwent progressive development and verification. These concepts contrasted radically with the ideas of his contemporaries, still entirely built around the principle of "action at a distance". Maxwell

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was the first to extend Faraday's ideas to include the quantitative wording and mathematical clarity, which they lacked originally.

According to the concepts of this "field of force" theory the reciprocal effects between electrical charges are spread out through the intervening space. Faraday's experiments had shown that these reciprocal force effects were influenced and changed by the presence of dielectrics anywhere within the intermediate space. The idea was firmly established logically that the space between the apparently independent reciprocally acting electrical charges is really a carrier of the potentials and energies distributed in it. These potentials and energies are not directly perceptible to us, but appear in the form of the forces which were described quantitatively by Coulomb's law.

Accordingly vacuum, "empty space", is also a carrier of potentials and energies, the presence of which is not bound up with the presence of matter. Through this consideration Coulomb's law, mathematically expressed, was shown to be an "integral law" which follows mathematically from "differential laws". Coulomb's law appears as the result, as the final effect of more primitive laws which refer to the "field", i.e., to space filled up with electrical potentials. Of course it is true that these laws, simpler to interpret physically, require very much more difficult mathematical tools for their formulation and exact understanding than does Coulomb's law, so simple to express. It must be established here—in a way which emphasizes the principle of continuity—how the state of the electromagnetic

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field at a given point is related to its immediate neighborhood, and how this electromagnetic state at each point in space and in its immediate neighborhood acts to produce variations in potential with time at that place (time rate of change).

2. *Electromagnetic Waves.* It follows logically from the field of force theory that a definite amount of time is necessary for the propagation of electrical effects. The assumption of an absolute distance effect permits the following representation. When an electric charge, which is acting on another far removed charge according to Coulomb's law, is suddenly displaced to another position, then instantaneously, without delay, the other, distant charge will experience the modified effect of the force, which corresponds to the new position. The latter charge "notices" at once that the position of the former one has been changed. But this idea of an instantaneous propagation of physical effects is incompatible with the idea of a "field of force". If the action of the force exerted by the first charge on the other remote one is effected through the intervening space—reaches the distant charge via the bridge of potentials filling the space between them—then only the field—the bridges—in the immediate vicinity of this charge will be modified to correspond to its new, rapidly changing position. This rearrangement of the field, which commences in the neighborhood of the charge, spreads out into space very rapidly. Nevertheless a finite time is required before this modification extends to the region of the other charge.

The electrical effects of a charge require a finite

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time for their propagation. If now we consider the case of a charge which not only undergoes a single rapid change in position but is repeatedly and continuously induced to swing back and forth, then the electric field never returns to a static condition. The electric field is transferred into a state of periodic vibration corresponding to the periodic oscillation of the charge—electric waves emanate from the swinging charge. At this point the “action at a distance” and “field of force” theories separate into their experimentally verifiable conclusions. The mutual actions of static charges can be interpreted both in the sense of “action at a distance” and of “field of force”. Despite the essential difference between the methods of representation, problems on static charges always yield the same results. This holds not only for mutual action of static charges according to Coulomb’s law but also for many other complex processes in the rich realm of electrical phenomena. The “action at a distance” theory is consistent with Faraday’s discoveries, and could be extended in its range of usefulness—with results that agree with experimental facts just as well as the “field of force” theory. It was only the assertions of the “field of force” theory regarding electromagnetic waves, which are said to emanate from oscillatory charges, that made a final decision about “action at a distance” and “field of force” possible, since these waves could not be reconciled in any way with the idea of “action at a distance”.

The history of physics contains no more impressive example of the creative force of theoretical thought in physics than the history of the discovery

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of electromagnetic waves. For these waves, which today rank among the most important problems and media of technical work and which assume a noteworthy position in the general framework of our modern life, were not discovered through experimental research. They were formulated on paper, deduced from the mathematical formulæ which Maxwell had begun to evolve as a quantitative description of Faraday's ideas. Only subsequently were they sought experimentally, and found by Hertz.

A more detailed treatment of Hertzian waves would be superfluous. Originally the discovery of a meditating theoretician, later observed by the experimental investigator, these waves are today familiar to the layman as a result of their technical application in everyday life. Everyone knows that radio waves have wave lengths that extend up to several kilometers. Actually there are electromagnetic waves of much longer wave lengths, but practically these are of little importance. Short wave transmitters utilize wave lengths of about a meter; ultra-short wave (ultra-high frequency) transmitters use wave lengths of the order of magnitude of a centimeter; and experimental results show that infra-red heat rays are simply still shorter electromagnetic waves, whose wave lengths equal only fractions of a millimeter.

On the basis of known experimental results, Maxwell was able to determine theoretically how great the propagation velocity of the electromagnetic waves he had predicted must be. His result led him to a bold inference through which an entire, hitherto independent chapter of physics was classi-

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fied under electrodynamics. Maxwell found that the propagation velocity of electromagnetic waves must be the same as the velocity of light; and he concluded that light is actually a form of electromagnetic radiation.

3. *Light.* Olaf Römer had determined the velocity of light as early as 1675. In observations that extended over several years he noted the entrance of the innermost of Jupiter's moons into the shadow cast by Jupiter and its emergence from the shadow into the sunlight. If it is correct that light requires a finite time to travel from one place to another then the entrance of one of her moons into Jupiter's shadow will not become visible on the earth until somewhat later. Likewise a measurable interval of time elapses before the sunlight, begun to be reflected by Jupiter's moon upon its emergence from the shadow, reaches the earth. If this moon, which requires $42\frac{1}{2}$ hours for each revolution around Jupiter, maintained a constant separation from the earth, its emergence from the shadow would become visible to an observer on the earth regularly every $42\frac{1}{2}$ hours. But while the moon has completed 30 revolutions, for example, the earth has advanced in its orbit so that its separation from Jupiter, and therewith the length of the light path, has been changed. Consequently the observer will see the thirty-first reappearance of the moon not exactly thirty times $42\frac{1}{2}$ hours after the first one, but earlier or later depending on whether the earth and Jupiter have been approaching or receding from each other. From this information Römer ascertained the value of

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the velocity of light. Measurements on the velocity of light with purely terrestrial tools did not become possible until much later, when experimental techniques had reached a higher state of development.

Light travels 300,000 kilometers (186,000 miles) per second; it could circle the equator almost eight times in a second; but it reaches the earth about eight minutes after leaving the sun, and requires about four and one-half years to travel to the earth from the nearest fixed star. It takes 100,000 years for light to traverse the milky way system rectilinearly. And astronomers have knowledge of systems related to the milky way, located far beyond it, from which light travels 100 million years before reaching us; thus we see these "nebulae" as they were 100 million years ago.

The mere fact that light has the same velocity of propagation as the electromagnetic waves predicted by Maxwell would not have sufficed to justify the proposition that light was a special case of electromagnetic radiation. But light had already been described as a wave radiation in Maxwell's times, and more refined optical experiments (concerning the "polarization" of light) indicated properties of light which conformed exactly to the law of radiation mathematically constructed by Maxwell.

Spectral resolution of light and the synthesis of white light from colored had already been observed by Newton in investigations which are no less worthy of admiration than his celestial mechanics.

But Newton did not consider light—like sound—to be a wave motion. He preferred the interpre-

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tation that a luminous body, such as the sun, constantly emits hail showers of very tiny particles and that this shower of light corpuscles is the basis for what we perceive as light. Another explanation, already worked out by Huyghens in Newton's time, was suggested by later research but was not experimentally confirmed until afterwards, although Newton himself had described experiments which could only be understood with the aid of this new idea.

If we imagine two hail showers falling on the same place simultaneously, or two machine guns bombarding the same target, the result is necessarily an intensification, an addition of their effects. In the case of light, however, there are cases where light coming together with light produces darkness. This phenomenon—called “interference”—was investigated in innumerable varied experiments; upon its practical application are dependent many of the most important observation instruments of modern physicists (e.g., spectroscopic “gratings”). The existence of these interference phenomena becomes understandable if one observes the intersection of the circles (waves) produced on the water's surface by two stones thrown into it. The circles continue through each other without being destroyed; but where the wave crest of one and the wave trough of the other come together, they annul each other. That is the basis of the interference in which two light excitations annul each other. These interference phenomena as we see them show that light is the result of a wave process. All interference effects ever observed, including their finest

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details, can be explained quantitatively by the conception of light as a wave motion, wherein, strictly speaking, monochromatic light always corresponds to a fixed wave length. Red light with a wave length of about .00076 mm. and violet at about .00038 mm. represent respectively the longest and shortest wave lengths visible.

In this physical picture of light processes there are no more colors; there are only oscillations in a colorless electromagnetic field. But we shall guard against the careless methods of expression that found favor in an earlier stage of natural scientific development and philosophical adjustment. We want to guard against a mode of expression such as the following: now the "existence" of light is disclosed and the coloration of light is recognized as an illusion—as something which originates in our brain. As we know, no less a figure than Goethe spoke out passionately against Newton's theses on the color of light. It is beyond the scope of this book to pursue any further the arguments that Goethe used and the conceptions he developed. But we shall consider his observations as a reminder not to be too hasty in our judgments.

Certainly the establishment of the wave properties of light has brought us no closer to the real existence of blue or red, although refined experiments have taught us of the existence of remarkable new properties of blue and red light. Just as when an object which has always been seen from the front is viewed from the rear for the first time; the new things that are learned are added to what was already known; but it would be erroneous

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to say that through this consideration of the rear side the "existence" of the entire object has been recognized and its front side has been proven an "illusion".

We shall still defer the questions which arise here and which in general concern the most profound problems of physical knowledge and thought. We shall still have sufficient opportunity to reconsider the questions of natural scientific doctrines.

4. *The Ether Problem.* This discussion, in striving to clarify the thought content of modern physics and to make its philosophical conclusions evident, is not bound to the historical sequence of development. Our attempt to follow logical relationships leads us along a zigzag path through historical development.

Long before light was recognized (Maxwell) as a special case of electromagnetic radiation, the problem of how light waves could pass through a vacuum had been pondered. Sound waves, in fact, produce vibrations of the atmosphere and cease to exist in the absence of air. But how can we explain that light oscillations can take place also in a vacuum? What oscillates here? To satisfy these questions a new hypothesis filled empty space with an obliging medium, fine, thin and all-pervading—the ether. Then the problem arose of inferring the nature of this ether from knowledge of the laws of light phenomena and conversely, explaining the laws of light by a mechanical model of the ether.

When these questions arose at the beginning of the last century the tools for their answers were

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already at hand in the highly developed mechanics of that time. Based on the mechanics of centers of mass, the basic concepts of which were described in the first chapter, a mechanical theory of a material medium which fills all space was set up. The theory of elastic vibrations and waves in gases, liquids and solids had essentially been established. Here we must differentiate between longitudinal and transverse waves; i.e., respectively between those in which the matter oscillates parallel to the direction of propagation and those in which the vibration is perpendicular to this direction. Gaseous media sustain only longitudinal waves, in which case each minute volume of the medium is periodically rarefied and compressed. Both types of waves occur in solid bodies. Light waves had already been proved—through the aforementioned experiments on the polarization of light—to be transverse, never longitudinal. Thus if the ether is to be considered as a material medium, it must be conceived of as a sort of solid body which opposes any rarefaction or compression with infinitely great resistance (possesses no “compressibility”). This result was surprising in view of the fact that the planets, as shown by experience, move on through this ether without encountering the least resistance. But if many other difficulties had not arisen this fact alone would not have proved decisive. In any case, not a single tangible new idea, not one suggestion for an experiment leading to new conclusions resulted from all the laborious experiments on the mechanical ether model.

Maxwell's classification of light phenomena with-

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in the comprehensive framework of electromagnetic processes produced a completely altered situation. There resulted not only a knowledge of entirely new relationships between light and other physical phenomena and regularities but a changed spiritual attitude toward these problems was facilitated. Maxwell had succeeded in establishing the regularity of electromagnetic waves—inclusive of light—with a completeness and mathematical clarity which do not suffer by comparison to Newton's law of gravitation. As Newton had, Maxwell could say, "Hypotheses non fingo". Through Newton's law all questions concerning the motion of planets, moons, comets, etc., became answerable without waiting for a possibly more thorough establishment and explanation of this law. Similarly, through Maxwell's law all questions falling within the region of validity of his theory could be answered precisely and independently of the problem of the mechanical explanation of the properties of ether.

Maxwell himself did not follow the principle "Hypotheses non fingo" absolutely; he had deliberated over various extensions for obtaining a mechanical ether theory. But the overall total direction of his work pointed to something entirely different. It was the influence of his discoveries which led more and more physicists to regard the entire problem of the mechanical ether model as fruitless and superfluous. For if it is possible to predict the result of any conceivable electrodynamic experiment, if electromagnetic processes can be grasped as readily mathematically as the motions in the planetary system—then what more do we want?

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Not only the method of thinking trained by materialistic philosophy but also that physical instinct, which had learned from nature the more profound significance of the physical "field of force" laws as against the "action at a distance" laws, resisted the recognition of Newton's (or similar to this, Coulomb's) law as a non-derivable physical elementary law. There remained only one counter argument in which traditional materialistic philosophy opposed Maxwell's theory, which already depended on the idea of a "field of force" and had clarified this idea with mathematical precision. This philosophy maintained that only mechanical laws, as evidenced in the pressure and collisions of atoms, are to be recognized as the true and final laws of nature, and that therefore only the reduction of natural phenomena to a mechanical model can yield a real "explanation", a real "understanding" and a real "recognition" of the existence of things.

Since Maxwell's theory appeared as a mere description of electromagnetic processes without really attempting to explain their laws, it must have startled the advocates of the mechanical explanation of nature when Kirchoff in 1876 began his lectures on mechanics with the famous sentence, that it was the function of mechanics "to describe the motions proceeding in nature completely and in the simplest manner." In that sentence he expressed a trend of thought which had already been amply explained and confirmed previously by Ernst Mach and which is usually designated as physical "Positivism".¹

¹ It should be noted that the spiritual scientific concept of "Positivism" has no connection with the physical.

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This reference, which showed that the ultimate aim of mechanics is simply a description of mechanical events—that it does not in any way lead us to any “understanding” of the “essence” of mechanical phenomena—stripped the defense of the mechanical meaning of the ether of its last weapon. When it became evident that belief in a separate appreciation of mechanical laws actually depends on habit only, all inducement for considering the mechanical laws as fundamental, like the Maxwellian electrodynamics, disappeared. The long since decided victory of Maxwell’s theory over the mechanical ether theory—conversely, modern physics traces mechanics back to electrodynamics—is therefore bound up with an impressive displacement of the philosophical attitude of physical investigation. The new approach can be characterized as a radical answer to the old. It relinquishes just that which previously was considered—be it in a vague sense or in the sense of the materialistic philosophy—as the true goal of physical research; namely the penetration into the heart of natural physical processes by stripping them of all the cloaks of outer appearance. In contrast we set a much more unassuming goal. We recognize that we can achieve our final purpose only by obtaining new data through experiments and by winning support for the prediction of the results of future experiments by a mathematical description of the experimental determination developed by the acuteness of theoreticians.

5. *The Relativity Principle.* The ether problem is closely related to the relativity principle as it was discussed in Chapter I. The existence of a lumin-

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iferous ether filling the empty interstellar space would make it still possible to speak in a certain sense of "absolute" motion; namely, motion relative to the fixed ether. Then the statement that light travels 300,000 kilometers per second would mean that light moves forth with this velocity relative to the fixed ether. In this case it must be possible to determine an absolute motion through optical-electromagnetic experiments, and we have already seen that the detection of an absolute motion is impossible through purely mechanical experiments.

This problem was thoroughly investigated experimentally. The most famous example is the experiment conducted by Michelson. He measured the possible difference in light velocities on the earth in mutually perpendicular directions with very great accuracy; and the resultant difference was exactly zero.¹ Obviously this experiment suffices to prove that there is nothing to be gained from the primitive idea of a fixed ether permeating interstellar space. All kinds of ways out were attempted, for example, the hypothesis that the ether surrounding the earth was carried along with the earth in its motion. But such an idea leads to very great difficulties. How far into interstellar space does this zone of ether carried along by the earth extend? How much ether does the sun carry along with it?

Maxwell pointed out that if the notion of a permanently fixed, space-filling ether were correct the absolute motion of the solar system must be detectable through observations on Jupiter's moons,

¹ Within the experimental error.

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in an extension of Römer's investigations. But experience denies this, since the sun is really moving relative to the fixed star heaven. Should it therefore be assumed that as the earth carries along its surrounding ether, the entire planetary system also draws along a self-enveloping ether cloud? Certainly the concept is becoming hopelessly complicated; and the many very accurate experiments conducted along these lines must lead only to a maze of most complicated results. That is not the case. The Michelson experiment and a series of further experiments which we shall touch on later in part yielded conclusions which in themselves are very simple and clear. The problem of developing an incontrovertible, logical connection between the varied (in themselves simple) experimental facts requires rather deep penetration into the lowest strata of our physical representation structure, which had to be revolutionized and transformed to agree with these facts.

“Aberration”, a phenomenon discovered by Bradley in 1727, provided very simple, impressive counter-evidence against the “carrying along theory”. If we stand on the front platform of a moving train in vertically falling rain we get wet despite the presence of roofing overhead. For the rain-drops falling perpendicular to the fixed earth (aside from all the secondary influences of the air motion produced by the moving train) are falling obliquely relative to the train. An analogous phenomenon is evident in the light of the stars falling on the earth, which leads to the conclusion that in the course of a year the fixed stars apparently execute

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small elliptical motions in the sky relative to the earth's circular motion.

Finally, let us consider the Doppler effect. When a whistling locomotive is approaching us we hear a higher tone than when it is receding from us. This is so because more sound waves sweep past our ear per second as the whistle approaches than when the locomotive is standing still or receding. An analogous phenomenon manifests itself in the case of light. From the displacements which the spectral lines in the spectra of the fixed stars undergo due to this Doppler effect, both the earth's annual motion and the motions of various fixed stars towards and away from us can be inferred. In the case of sound waves the magnitude of the Doppler effect is not only dependent on the relative motion of the sound source and the listener, but on the motion of both relative to the atmosphere. Correspondingly, if there were a fixed ether, one should be able to recognize absolute motions from the optical Doppler effect. Actual experience shows that this is not the case, that the optical Doppler effect depends solely on relative motion and furnishes no possibility of determining an absolute fixed ether. We can not summarize here the abundant detail of corresponding experimental facts which bear out the relativity principle, not only in mechanics, but in all branches of physics.

But even with this determination—which deals the ether representation a death blow—we are still far from understanding the problem; it is now really posed for the first time. An attempt to describe our complete optical-electromagnetic knowl-

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edge coherently in the all-inclusive form of the principle of relativity encounters tremendous difficulties. To surmount these we must revise the usual, apparently indispensable concepts which to us are most self-evident. For though it is simple to say that the relativity principle is also valid in optics, we must accustom ourselves to the idea that light always has the same velocity relative to any moving body—therefore, that the assertion “that light travels 300,000 kilometers per second” not only holds true for a particular condition of motion of the observer but for all conditions of his uniform rectilinear motion. But how can this “principle of the invariance of the velocity of light” be established free from contradiction when elementary thought habits assume that if we speed ahead in a space ship at 40 kilometers per second behind a light ray the velocity of the light ray relative to us would appear diminished by the 40 kilometers per second?

6. *The Theory of Relativity.* It required all the acumen of the greatest physical thinkers of our time to solve this puzzle. Modern publicity frequently supports the opinion that the so-called “theory of relativity”, in which these questions are cleared up, is a quite personal, private discovery of the famous physicist, Albert Einstein. Whereupon they usually conclude that the challenging position taken by the Third Reich toward Einstein personally with respect to political views must necessarily result in a challenge of the theory of relativity. This is a misunderstanding. It should be noted that a number of other investigators also produced

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definite contributions to the theory of relativity (Poincaré, Lorentz, Minkowski, Planck, Hilbert, Weyl, Eddington, etc.) and further, that the physical knowledge expressed in the theory of relativity would have been an inescapable logical conclusion from the experimental facts if Einstein had never lived. An attempt at a systematic explanation of the theory of relativity would exceed the bounds of this treatment. Just a few points are singled out to help us examine the philosophical attitude of modern physicists more thoroughly.

If we look out of the window of a train traveling 80 kilometers per hour at another train traveling in the opposite direction with the same velocity, we can not determine our train's velocity relative to the earth by seeing only the other train. The only thing we can measure is our velocity relative to the second train—which relative velocity is obviously 160 kilometers per hour. What is the basis for our conviction that this is the case—a conviction of which we are so certain that not a single person will bother to actually determine it by measurement? We possess very deeply rooted thinking habits that impel us to this opinion so forcefully that we are wont to consider a divergent result as merely logically foolish. As is known, Kant developed the clever idea that our concept of nature is conditioned essentially not through inherent qualities of the objects of nature but through changeless thought patterns not derived from experience, but incorporated by us into observations and investigations of nature. He not only expressed these ideas in a general form; but he also analyzed these ways

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of perception completely, attributing them invariably to the nature of the human mind.

The physical experiences which lead to the theory of relativity exhort us to a fundamental distrust of constructions which denote certain experimental data as independent and invariant. For the theory of relativity teaches us to recognize that a number of just such measurements are capable of (and require!) modification and generalization. Previously there existed the inclination to believe in the certainty of their accuracy independently of experimental experience. Let's take the above example of the two trains again: today we know that the proposition that the velocity of the two trains relative to each other is equal to the sum of their (oppositely directed) velocities relative to the earth is not really precisely correct. Actually this relative velocity is a little smaller than the sum of the two. In this example the difference is imperceptibly small; but, if instead of the railroad trains we take two bodies which are moving with much greater velocities quite a considerable difference results. If each of the two trains were traveling at a speed of 200,000 kilometers per second (two-thirds of the velocity of light) the relative velocity would only amount to 276,923 kilometers per second instead of 400,000. There is experimental evidence to confirm this. The former opinion that appeared certain without experiment was disproved by investigation which confirmed it as practically correct only under certain conditions (namely, only for velocities that are much less than that of light). This extension and change of ideas, that appeared

to us as invariably self-evident, and the development of new concepts, proven necessary by experimental experience, made possible the very great usefulness of the theory of relativity.

In passing we noted the "positivist" attitude toward the problem of physical knowledge—merely seeking a summarizing description of experimental facts instead of an alleged explanation, penetrating into the essence of things. This makes it necessary to check most rigorously whether all our assertions, suppositions and problems fit completely into a system of pure description of observed results. Any statement which falls beyond this limit—especially any attempt to express something about the so-called "essence" of physical things—must be eliminated and declared basically meaningless. It is overrating the significance and scope of physical knowledge to believe it possible to make statements that are not confined to a description of experimental measurements—may these measurements be confirmed, suspected, questioned or contradicted. Modern developments have shown over and over again with finality that only this radical liberation of "senseless" opinions brought about by positivist criticism gives scientific thought the necessary freedom to adapt its ideas to the greater and more difficult demands placed on it; demands due to the high precision applied to the experiences of daily life by modern experimental research and to the disclosure of new, separate fields which lie completely outside of our previous experience and thus completely beyond the power of comprehension of our customary, acquired modes of viewing. Concep-

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tions which appear most self-evident to us are frequently just the ones which prove to be the greatest obstacles to the transformation of our ideas necessary to adapt them to the new experiences.

The theory of relativity includes one of the most wonderful examples of the liberating force of this positivist criticism on our opinions. What is meant by the phrase, two events occur "simultaneously"? No problem exists when both events take place in spatial proximity, and can thus be seen in the same glance. But what is meant by the assertion that the falling of a stone on the earth occurs "simultaneously" with an event on Sirius? The key to the theory of relativity lies in the insight that, to make any sense at all, the definition of the "simultaneity" of two events widely separated in space must be made concrete, must be transposed into an experimentally verifiable form of expression. No method but the following remains to effect this definition. At the instant the stone falls on the earth a light signal is emitted; at the same time when the imagined event is taking place on Sirius a light signal is sent out from there; and when the earthly signal reaches Sirius, a light signal is sent back from there at once. The reflected light signal returns to the earth again about eighteen years later. If the time elapsed between the earthly event and the arrival of the first light signal from Sirius amounts to nine years (more exactly, if it is just as great as the separation between the times of arrival of the first and second light signals from Sirius) we say that the two events, on Sirius and the earth, occurred "simultaneously".

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If signals existed that were propagated more rapidly than light signals these would naturally be used for the definition of simultaneity. If the theory of "action at a distance" were correct the difficulties of defining simultaneity would disappear in general. For then it would be possible (in principle—the question of the technical accomplishment is an independent one) at the instant the stone fell on the earth to dispatch a signal which would become perceptible on Sirius without any loss of time at all—perhaps through the Coulomb type of "action at a distance". But we have accepted the bases of the "field of force" theory, according to which all physical effects require a finite time of propagation—an idea of decisive meaning for the theory of relativity. By the "field of force" theory the velocity of the signal can not exceed a definite limit; and today we know that light possesses the greatest signal velocity possible.

After the above definition for the notion of simultaneity has been given, mathematical investigation leads to the perception of simultaneity as a relative concept. Viewed from the abovementioned train, which is traveling at 200,000 kilometers per second, the two events on the earth and Sirius would no longer take place simultaneously, since an experimenter traveling in this rapidly moving train would obtain a different result in executing the measurements pertaining to the definition of simultaneity than we would on the earth.

An example illustrates the remarkable results which ensue. Consider a space ship traveling with an enormous velocity—almost equal to that of light.

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Suppose that the crew returns to the earth after a one year voyage at a speed slightly less than that of light.¹ Their watches, taken along in the space ship, have measured just one year of time; their one year stock of provisions has just been used up; and their hair has greyed just about as much as would be expected from the hardships of a one-year trip in interstellar space. But, arrived on the earth the crew finds that in the meantime the human race has aged one hundred years.

These are very remarkable assertions; and our thinking which finds it too difficult to leave familiar paths, is inclined, at first, to view them as pure nonsense. But that is prejudiced. The sum of these propositions forms a self-contained, incontrovertible logical system; a system which does not stem from the imagination, but is based on the irrefutable facts of experimental experience.

Finally, it should also be mentioned that in connection with the theory of relativity—in a generalization of theory which extends far beyond what we have discussed until now—the problem of tracing Newton's gravitational attraction and "field of force" laws back to fundamentals was solved. The fact that the "gravity mass" of any body exactly equals its "inertia mass" is conclusive for this solution. Otherwise expressed, in ideal fall (in a vacuum) all terrestrial bodies experience exactly the same acceleration. Thus one can say that a physicist in a high elevator which is released and falls down unhindered will make exactly the same observations as another physicist who moved uniformly,

¹ Namely, 0.05% less than the velocity of light.

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in a straight line through the universe in a space ship in a region where the gravitational attractions of the stars are ineffective because of their great distance. To the physicist in the freely falling elevator the weight of any body would be annulled; and the physicist in the space ship, when his motion was accelerated, would find the same effects in his ship as the earthly gravitational field exerts. This consideration leads to a more penetrating understanding of Newtonian gravitation. We must deny ourselves more exact treatment of this. One thing, though, deserves emphasis in connection with these considerations: the complete validity of Euclidian geometry in actual physical space must be denied; only approximate validity should be ascribed to it, since more general geometric notions, which we owe to the German mathematician Riemann, agree more closely with real physical space (Einstein). This also shows that we obstruct the path of physical knowledge when we consider opinions and methods of perception, which appear self-evident from long familiarity, as irrefutable, invariable and independent of physical experience.

CHAPTER III

THE REALITY OF ATOMS

1. *Speculative Atomism.* Actual proof of the reality of atoms is an achievement of this century; even at its beginning critical consideration required the confession that atoms, although investigators spoke of them, were still no more than a stimulating and useful hypothesis, which in the final analysis was unproved and possibly unnecessary, perhaps even misleading. Although the idea of atomism was important and fruitful at the very beginning of western natural research, this idea did not originate from western research itself; just as we borrowed the model for mathematical thinking from the Greeks, we took the atomistic interpretation of nature from them.

Nothing exists — Democritus taught — except atoms and vacuum; everything else is imagination. These innumerable atoms, indestructible and invariable elementary constituents, are to be considered the basis for all beings and events in nature. Individual atoms possess invariable geometric form and motions which fluctuate due to the pressure of and collision with other atoms. In all changes in the structure of nature the atoms are always preserved; from nothing comes nothing; nothing which exists can be destroyed; change is merely combination and separation of parts. The differences of all things stem from the diversity of their atoms in number, magnitude, structure and arrangement.

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Since the movements of each individual atom are regulated according to natural law, nothing arbitrary can happen in all nature; nothing happens accidentally, but everything from a cause and of necessity. Our rough senses can not recognize these amazingly fine elements in their true nature and form, but experience their effects only vaguely. "Only in the imagination does sweetness exist, in the imagination bitterness, in the imagination heat, cold, colors; in reality nothing exists but atoms and vacuum."

This is marked evidence of that "decoloration" of the world, the assurance that all direct sensory observation is an illusion and that a knowledge of the true status of things must lead us to a picture in which nothing remains but the geometrical form and mechanical motion of the atoms. These idea forms of materialistic philosophy introduce the possibility of considering all events in nature as results of strict regularity; the gist of the basic concept of natural scientific thought is anticipated here in general and is thoroughly formed for the first time. On the other hand we must not forget to recognize how radically this philosophy opposes religious representations of its time. For the Greeks every stream was a God; in the springs lived the nymphs, in the woods the horned Pan, and in caves and caverns resided demons. This entire mythological picture of the world, which suspected the arbitrary and incalculable influence of demoniacal powers in every natural process, was pushed aside by the powerful conception of a picture of nature of stricter regularity. Epicurus, who renewed Demo-

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critus' teaching, and who in his thinking and conduct of life combined a rationalistic, vigorous attitude with a very cultivated, fine-spirited being, was not so brutal as to deny existence completely to the Gods. He let them continue as blessed, immortal beings, occupied with themselves, and never infringing upon the workings of the world—these workings being developed according to the mechanical lawfulness of atomic motions in strict, definite sequence. In a great didactic poem "De rerum natura" the Roman Lucretius explained completely the ideas of atomistic regularity for all the fields of nature known at that time. These teachings were made known to western scholars in connection with the humanistic studies of the Renaissance; Gassendi, principally, introduced Greek philosophy into western science.

Let us consider the ideas which Newton, together with Gassendi, applying the divergent theories of Descartes, formed about the construction of matter. F. Dannemann explains them as follows in his historical work¹ on the natural sciences: "He considered it most plausible, that it (matter) consists of solid, impermeable, moving particles. Since natural bodies, e.g., water, are invariable in their properties, the particles of which they consist must neither be able to be used up nor destroyed. The variation of material things is to be laid exclusively to the separations, combinations and movements of those invariable particles." These are, as is obvious, exactly the concepts of materialistic philosophy,

¹ *The Development and Inter-relation of the Natural Sciences.* Four volumes. Leipzig 1910-1913.

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almost unchanged, just as Democritus stated them. But Newton was—outside of natural science—in no wise an adherent of materialistic theories. For him these ideas meant nothing but a clue to physical research; he did not see in them the support of radical, world-viewing results.

2. *The Natural Scientific Evaluation of the Atomic Concept.* Dalton first recognized and effectively utilized the stimulating force of the atomic concept and its ability to guide future physical research. To him we owe the use of the idea of atoms for understanding basic regularities of chemistry. Chemistry makes a sharp distinction between mixtures of different substances and chemical combinations. A mixture—as, for example, a solution of sugar in water or a mixture of nitrogen and oxygen—can include arbitrary (within certain limits) relative proportions of the constituents. In a nitrogen-oxygen mixture the portion of oxygen can be varied continuously by addition or removal; correspondingly, the mixture exhibits properties somewhere between those of pure oxygen and of pure nitrogen, depending upon the relative concentration. Also, the mixture can be separated into its constituents through relatively superficial means. In a chemical combination entirely new properties appear, which can be quite dissimilar to those of the constituents. The proportions of the components of a chemical compound are quite stable and cannot be varied continuously. Thus exactly 16 grams of oxygen always combine with 2.016 grams of hydrogen to form water. Another chemical substance, hydrogen peroxide, can be formed from

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2.016 grams of hydrogen and just 32 grams of oxygen. It is striking that exactly twice as much oxygen is utilized in the second case as in the first; and on the basis of the atomic concept Dalton found a clear explanation for such facts, which occur similarly in all chemical combinations. His explanation was as follows: The "molecule" of water, i.e., the smallest possible particle of water, contains only one atom of oxygen; the molecule of hydrogen peroxide however contains two atoms of oxygen, while it contains just as many (two) atoms of hydrogen as the water molecule. Here we arrive at the distinction between atoms and molecules; we designate the smallest particles of chemical compounds as molecules, which for their part consist of atoms of the chemical elements. According to Dalton's ways of thinking a comprehensive study of proportions by weight in chemical compounds rendered the determination of the relative atomic weights of all the elements possible. The "atomic" weight of oxygen is arbitrarily designated by the value 16, whereupon hydrogen acquires the atomic weight 1.008 and every other element, similarly, receives a definite atomic weight derived from chemical weight relationships.

The regularities which the gases exhibit, which in the case of sufficiently small densities assume an "ideal" form, proved very helpful for the clarification of these ideas; for example, in the sense that a gas mass contracts to one-half its original volume when, with constant temperature, the pressure impressed upon it is doubled. Criteria existed for the hypothesis that not only in compounds but also

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in a gaseous element such as nitrogen the particles moving at random through space are not necessarily identical with atoms; in nitrogen, for example, each "molecule" of the gas consists of two atoms. In the chemical combination of gases (with constant pressure and temperature) there is a simple relation between proportions by weight and volume relations (proportions by volume) between the chemical compound and the still uncombined constituents. To fit these facts Avogadro introduced the explanation that equal volumes of all gases measured at constant pressure and temperature always contain the same number of molecules. Based on this "Avogadro's principle" a "molecular weight" can be determined for each gas independent of chemical weight relations. The molecular weight of a chemically homogeneous gas is equal to the mass of 22.4 liters of this gas measured in grams at one atmosphere of pressure and a temperature of 0° C. Experience shows that values obtained in this way correspond with the chemically defined atomic weights. In many elements, e.g., the metals, this molecular weight is exactly the same as the atomic weight; thus metallic vapors are "monatomic". In the aforementioned nitrogen, however, the molecular weight is exactly double the atomic weight. And in water it equals 18.016 ($2 \times 1.008 + 16$) in accordance with its above-described chemical composition. These ideas are further verified by simple relations of molecular weights such as "diffusion velocities", or by the characteristic difference between the specific heats of "monatomic" and "polyatomic" gases. None of these, it must be emphasized, are

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proofs for the correctness of the atomic concept; but they are proofs for its usefulness. The atomic idea describes very plainly a large number of important and comprehensive regularities, thus facilitating greatly our progress with these phenomena.

Crystallography furnishes evidence of further regularities which are certainly clearly explained by the atomic idea, though they too do not lead to proofs for the reality of the atom. In the crystalline state of matter the atomic concept suggests a regular grouping of the atoms or molecules, alongside of each other and arranged in layers. This view induces important results; on this basis the variety of possible forms of crystals are shown mathematically to be limited very considerably. The completion of this mathematical proposition yields the wonderful result that according to the atomic concept there should be no more nor less than 32 different "crystal classes" which are defined by different properties of symmetry. Actually this confirms precisely the experience of mineralogists; there really occur in nature all the crystal forms (crystal symmetries) which are compatible with the atom idea, but not one single one which contradicts it. The so-called "law of rational indices" discovered by the mineralogists formed an important adjunct to this original consideration, which is related only to the symmetry properties of different crystal forms. If we imagine the crystal as built up of a regular stratification of layers of atoms, then its outer boundary surfaces could never lie so that they partially cut through the atoms. The limits for the possible positions of the bound-

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ary surfaces given by this view are exactly equivalent to the requirements which the law of rational indices places on the position of the crystal surfaces.

Such experiences must necessarily encourage the more and more energetic pursuit of the atomistic notion—which intrinsically was so clear—even though tangible proof for the reality of atoms was still lacking. Actually the theoretical development of the atomic concept was furthered extensively by the most able physicists. We have already mentioned ideal gases and indicated how the gaseous state of aggregation should be represented on the basis of the atomic theory; the molecules of a gas are completely separate from each other; each one moves along with high velocity until it meets another one, and then, in elastic rebound, their direction of motion and speed change. The continuous impact of countless molecules on the walls of the enclosing vessel produces the pressure of the gas, perceptible to us with our rough tools. These ideas were elaborated thoroughly (Clausius, Maxwell) and our understanding of the gaseous state of aggregation was developed very clearly and completely. Whereby the proof resulted that Avogadro's principle, first only speculatively suspected, must necessarily be correct if the atomic hypothesis proves at all valid.

The discovery of the energy principle (Mayer, Joule) further strengthened confidence in atomism. It was recognized that mechanical energy, which disappears through friction or the like, reappears in the quantity of heat produced—in such a way that a definite amount of consumed me-

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chanical energy corresponds to a definite number of calories of heat. Conversely, according to the same conversion relation, in steam engines quantities of heat are transformed again into mechanical kinetic energy. This conversion of mechanical energy into heat and its converse can be considered quite consistent, in the sense of "macro-physics". Whereupon one must establish that energy, which has proved indestructible, can assume both the form of a quantity of heat and of mechanical energy. The "macrophysical", "phenomenologic" heat theory thus arrived at is entirely sufficient for answering all the questions encountered in connection with heat engines, and with heat conversion in chemical processes.

But further thought is suggested to give the process of the conversion of mechanical energy into heat a clear interpretation in the light of the atomic theory. In a gas, as was represented above, the concepts of heat and temperature are not applicable to the individual molecules, but only to the gas mass as a whole. In an individual molecule only the kinetic energy, i.e., its velocity of motion, or at best also its rotation, can be changed. Thus, if energy is added to a gas mass, which appears macrophysically as added heat, it can only mean that the average energy of motion of the gas molecules has increased. The exact determination of the connection between the average energy of motion of the gas molecules and the temperature of the gas is a part of the theoretical investigations on the "kinetic theory of gases", which has already been discussed.

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Similarly, in a solid body, a crystal perhaps, the temperature and heat energy contained within it are conceived of as mechanical energy of its molecules or atoms. Although in their regular arrangement in layers no one atom can leave its place, fine vibrating motions within the crystal—possibly similar to the fine vibration of a heavily traveled steel bridge—are still possible. If these vibrations within the crystal are so small that they are not perceptible to us as mechanical motion, we do note the energy of these motions—as heat content which manifests itself in the temperature of the body. (If the atoms contained in each small piece of the crystal move by very small amounts in random directions, the whole crystal appears motionless to our macrophysical senses.)

Apropos of such thought processes was Boltzmann's atomistic interpretation of a remarkable regularity in heat phenomena. If we imagine that a planet's motion is interrupted and the planet then is induced to move in the opposite direction with the same velocity, it will retrace its entire elliptical path in the opposite direction after the reversal. This is an example of the fact that all purely mechanical motions are, as we say, reversible. The upward motion of a stone, thrown from the earth, (in the ideal case) until its point of reversal is an exact temporal mirror image of the subsequent downward motion. Similar reversibility—which can also be denoted as a physical “symmetry of the positive and negative time orientation”—exists in all purely electromagnetic properties.

But when we move a body over a table surface

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against frictional forces and heat is generated thereby, there is no reason to expect that in moving the body backwards along the same line the converse is true—that the heat energy will change back to energy of mechanical motion. Or take an electric current which flows through a wire and produces heat—when it flows through the wire in the opposite direction it again produces heat; the heat energy does not change back into electrical. These are examples of irreversible processes. Another example of such a process is the mixing of two liquids; in most cases these intermix by themselves, but this process never runs backward of itself. A further example of importance to us is the following: if a gas filled vessel is introduced into an evacuated one and is opened there, the gas diffuses throughout the entire available volume. It is not impossible to restore the original conditions; the larger vessel can be evacuated again by pumping and the gas can be compressed into the smaller one. But this does not constitute an exact reversal—a temporal reflected image—of the first process; and it can be considered that for the restoration of original conditions after any irreversible process a definite “compensation” must be included (Clau-sius). In the steam engine, which undertakes to convert quantities of heat into mechanical energy, there does not occur a simple reversal of the process of the production of heat through friction, but each steam engine functions according to a scheme similar to the following: a certain amount of heat is removed from a heat container maintained at a high temperature. A fraction of this amount is changed

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into mechanical work, while the remainder is conducted into a heat reservoir of lower temperature. As "compensation", therefore, for the conversion of heat into work there occurs the transfer of a quantity of heat from a hotter body to a colder one—i.e., therefore a process which nature could perform "irreversibly" itself, since in heat conduction the heat always flows from higher to lower temperature.

The occurrence of such "irreversible" processes among heat phenomena posed a very difficult problem for the "kinetic theory of heat"—tracing back the laws of heat to the mechanics of atoms. For purely mechanical processes were shown to be always reversible, which makes it appear impossible to trace these irreversible heat phenomena back to mechanical properties. The solution of this difficulty, achieved through Boltzmann's perspicacity, runs as follows: in an aggregation of many similar particles, such as are attributed to every physical system by the atomic theory, there is no point to pursuing the motion of each individual atom or molecule; it is only important to us to observe the average statistical behavior of large numbers of atoms. Thus statistical concepts are necessarily introduced into the consideration and we must determine which (defined in a rough statistical sense) events are to be considered as especially probable (thus as occurring very frequently) in comparison with other conceivable processes.

For our example this signifies that when the small gas filled vessel is opened in the large empty one "it is extremely probable" that the gas will

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stream out and distribute itself uniformly in the large vessel. Strictly speaking it cannot be definitely known that this will happen; indeed, to view the processes of motion in the gas mass with the same complete certainty achieved for planetary motions one must know quite exactly the position and velocity of each individual molecule at the beginning of the experiment. The fact that, instead of this, we simply denoted the initial condition of the experiment statistically stipulates that we can not predict its further progress with complete certainty, but only with very great probability.

The reversibility of pure physical processes, which according to the atomistic conception is the basis for macrophysical heat phenomena, depends upon the existence of an exact reversal, an exact temporal reflected image for every process—whereby it can happen that the gas mass distributed in the abovementioned large vessel contracts into the smaller one, in an exact reversal of the normal process. No one can guarantee that this is completely out of the question; but we can show that such an event is extremely improbable—mathematically its probability is expressed by an infinitesimally small number. Thus it becomes clear that despite the fundamental reversibility of atomistic elementary-processes, yet, on a large scale, in macrophysical events, practically irreversible phenomena take place.

Another instructive example of an irreversible process is the mixing of two gases or liquids with each other. According to the kinetic-atomic theory this problem is somewhat similar to the one wherein

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two types of balls—red and white ones for instance—are thoroughly shaken up in a sack. If the red and white spheres are carefully separated initially, they will become completely mixed up after further agitation. If, then, we continue to shake, it is possible in principle that the original separation of red and white balls will be restored—but practically this possibility is of little moment since it would require shaking for astronomically long periods of time before this “spontaneous separation” could be expected with appreciable probability.

A quantitative measure for the irreversibility of a thermodynamic process (from a purely macrophysical standpoint) can be specified in the form of “entropy”—a quantity which always increases to a maximum in irreversible processes and does not decrease again (Clausius). According to Boltzmann this entropy can now be defined through the atomic concept as a measure of the disorder in an atomic aggregate. As the above example of the mixture illustrates, in an incompletely “disordered” system, the probability of further disorder is extremely great.

3. *The Limits of the Divisibility of Matter.* Everyday experience, which appears to show unlimited divisibility of matter, through simple refinements makes it certain that atoms must be extraordinarily small, and that therefore the number of atoms in a gram of any substance must be enormously large. For an exact measure of this quantity we use the so-called Loschmidt number. As a “gram-atomic weight” of an element we denote a mass of a number of grams equal to the atomic

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weight; the Loschmidt number is the (equal for all elements) number of atoms in a gram-atomic weight. Evidence for the divisibility of matter can be obtained by distributing a minute amount of a strong-scented substance (mercaptan) in a large quantity of air and then determining to what degree of dilution the odor can still be perceived; or by dissolving a strongly colored liquid (eosin) in a relatively large quantity of water and then noticing to what degree of dilution a uniform coloration of the water remains perceptible. A still more suitable experiment involves the use of a very dilute solution of fluorescein, a substance which fluoresces strongly in incident light. Extremely small volumes of the solution are examined with a microscope to determine to what degree of dilution a spatially uniform fluorescence can be detected. From such observations it can be inferred (Perrin) that the Loschmidt number is definitely greater than 10^{21} (a 1 with 21 zeros after it).

But quite simple, daily experiences occur that indicate the limits which its atomistic structure places on the subdivision of matter. These involve utilization of very thin membranes of matter. Gold leaf, which is used for gilding purposes, is hammered down to an exceptional thinness—when held against the light it exhibits a greenish translucence—of about 100 millimicrons (a million millimicrons make a millimeter); and yet this thickness is still far removed from the ultimate limit. But there exist direct indications for the atomistic constitution of matter in commonplace, familiar soap bubbles, often formed when washing by a film of soapy

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water stretched between the thumb and index finger. These bubbles iridesce in variegated colors, whose diversity and rapid shifting is evidence of the variations in the thickness of the bubble with position and time. Small dark spots appear in a thus colored bubble, which at first may be considered as holes, but which in reality are enclosed by still thinner soap films. If bubbles like this are produced in a solid frame instead of in the hand, and if they are protected from evaporation in a vapor-filled enclosure, they can be preserved for days. Newton had disclosed that inside these black spots—i.e., this membrane which weakly reflects light—still blacker, thus still thinner membranes are formed. The thickness of the thinnest membrane obtained by Newton was about 6 millimicros, about 20 times thinner than gold leaf. But the next thicker membrane obtainable, just before this thinnest one, is of exactly double thickness. This provided a tangible indication of the molecular structure of this skin substance; obviously, the thinnest membrane represents a single layer of molecules, while in the next thinnest one two layers are piled together. A very thin film can be produced more conveniently by allowing a minute amount of oil to spread out on a large water surface. The familiar iridescent films which oil forms on water correspond in their thickness approximately to the usual soap bubble. Much thinner oil films which are no longer directly visible but can be recognized with simple tools can easily be formed. In these thicknesses of about 1 millimicro have been reached; and in these it has again

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been shown that the thicknesses of the finest films are not continuously variable. As in the soap bubbles, we find a quite definite thickness prescribed for the thinnest, second thinnest, etc. oil film (for a definite previously determined type of oil). The limits of the divisibility of matter have actually been reached here.

Further highly informative investigations were performed on very small corpuscular particles. Here the invention of the ultra-microscope rendered important service; it made visible not only the form, but also the position and motion of particles which cannot be "seen" in the usual sense, since there are limits, defined by the nature of light, for the optical observation of very small objects. Bodies of dimensions smaller than the wavelength of visible light cannot be "formed" in any way by light rays; cannot be made visible in their true form. The ultra-microscope, through an ingenious device, made it possible to detect optically the presence of particles which are somewhat smaller than the wavelength of visible light.

For the fundamental task—to prove the reality of atoms experimentally—two types of investigations in particular have rendered real contributions. If very small particles are placed in a liquid it appears that they do not sink rectilinearly to the bottom and remain there but rather they move through the liquid in an irregular, erratic manner. The motion becomes more intense the higher the temperature of the liquid is raised; but it is independent of a minor agitation of the enclosing vessel or of other accidental disturbances. Also, if left

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undisturbed, the erratic motion of the particles continues for days or years. This Brownian movement serves as a direct proof for the correctness of the proposition, set up by the atomic theory, that the heat content of a body is to be conceived of as an internal motion which is so fine that it cannot be macrophysically detected as such. One must not conclude that there are very fine motions or currents in the liquid which produce the Brownian movement of the suspended particles. That would lead to the idea that the motions of a throng of closely neighboring particles were somewhat similar as is the case with dust we see around us in the sun's rays. In Brownian movements two approaching particles in a liquid are completely independent of each other, and thus separate again very soon. This shows that the hidden motions in the liquid, the permanent presence of which must be regarded as characteristic of the heat condition of the liquid, are completely "irregular" and macrophysically absolutely imperceptible.

Brownian movements have become the subject of many experimental investigations, for theoretical considerations had shown (Smoluchowski, Einstein) that its precise observation permits definite conclusions about the motions of atoms and molecules, through irregular collisions with which the particles in Brownian movements are driven around. It was possible to infer from investigation of Brownian movements how great the average kinetic energy of the individual molecules must be. And since the total heat energy contained in the liquid is equal to the sum of the energies of the

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individual molecules, we can infer how many molecules there are in a given volume. This leads to a determination of Loschmidt's number.

Related investigations and considerations are also feasible in many kinds of "fluctuation phenomena". Imagine an armor plate suspended from chains and blown upon by a very strong, uniformly operating sand blast apparatus; the plate will be forced from its equilibrium position by the pressure of the blast and will then hang in a slightly different position. Now, we remove the sand blast apparatus and by bombarding the plate with machine guns exert the same total pressure on the middle of the plate; the armor, struck over and over again by the single shots again assumes the displaced equilibrium position, this time continuously oscillating irregularly about this equilibrium position. Observing just these oscillations, one can determine the strength of the single blows striking the plate. Similarly in many types of physical apparatus very fine irregular fluctuations can be observed and from them the magnitude of the Loschmidt number can be determined. In the very fine physical apparatus the presence of the irregular heat motion of the atoms can be detected; thereby most varied methods can be utilized for determining Loschmidt's number. The values of Loschmidt's number obtained from all such investigations have always agreed within the limits of their accuracy.

The following describes the second possible way of determining Loschmidt's number from investigations on very small particles: the density of the earth's atmosphere decreases, as we know, with

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increasing height. Imagine two very high cylinders—about 100 kilometers high—to be filled respectively with two different gases, perhaps oxygen and nitrogen. It is demonstrated that in the gas whose molecules are heavier (oxygen) the density decreases outward from the earth's surface more rapidly than in the other gas. The gas molecules are hindered by their kinetic energy from simply accumulating on the bottom of the vessel, i.e., forming a liquid. But the heavier they are, the stronger is the effect of gravity forcing them downwards and thus the more rapidly does the gas density decrease with increasing height above the earth's surface. The mathematical law relating to this states that the comparison of the decrease in density in the two cylinders depends solely on their molecular weights.

This was most useful in its application to the production of an artificial gas in which the actual mass of the individual molecules is known. Perrin laboriously produced large quantities of small resin pellets of equal weight. He obtained these resin particles from an emulsion which originally contained particles of the most varied magnitudes; but by an ingenious procedure, involving painstaking work, he was able to separate out particles of corresponding mass whose diameter was from 200 to 300 millimicrons. These particles were then placed in water. (We know that with sufficient degree of dilution dissolved substances, e.g., sugar in water, behave analogously to the ideal gases.) Thus, the resin particles placed in the water represented an ideal gas and vessels a kilometer high

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were no longer needed to determine the decrease in density with increasing height with this artificial gas; even in small containers these artificial gas molecules, enormously heavy in comparison with usual molecules, crowd together noticeably at the bottom. Through measurement of this effect and comparison with the known decrease of atmospheric density with increasing altitude it is possible to compare the directly determined mass of these artificial, huge molecules with the masses, absolute values still unknown, of the chemical molecules present in the atmosphere. Thus a new approach to the weighing of molecules—or differently expressed, to a determination of Loschmidt's number—is reached.

The numerical value which resulted from these different determinations of Loschmidt's number (and from further determinations still to be discussed) is 6×10^{23} (a 6 with 23 zeros after it). If the hydrogen atoms contained in 100 grams of water were distributed over the entire earth's surface, one atom would fall on each square centimeter.

4. *The Conclusive Proof.* Finally we come to the experiments in which single atoms are actually isolated and made, in a manner of speaking, tangible, so that there is no longer any possible doubt concerning their real existence.

Let us begin with Laue's famous discovery of crystal interference. Modern workers in physical optics and spectroscopy no longer use only prisms for the spectral resolution of light; the diffraction grating has become much more important. When numerous lines at equal, close intervals are scribed

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upon a polished surface, a monochromatic (including just one wave length) light ray will neither be reflected from this surface as from a usual mirror nor as from a rough surface which reflects diffusely toward all sides. The ray is reflected in a series of definite directions which vary according to its wave length; in all other directions there is no reflection because the light excitations traveling in these other directions mutually annul each other by interference. This knowledge (a special interference experiment) gives us, as previously mentioned, the clearest and most obvious proof for the wave character of light and makes it possible to determine the wave length of the light just from a knowledge of the spacing of the grating lines. (In common gratings this is between a hundredth and a thousandth of a millimeter.) Conversely naturally the separation of the rulings on the grating, if by chance this value is not known, can be determined from the reflection produced by this grating with light of known wave length.

X-rays, on traversing crystals, exhibit remarkable interference effects which are related to those of the "line grating" described but are considerably more complicated. The discovery of these effects proved two things with one stroke; first, that X-rays are a wave radiation; and second, that crystals possess a fine grating-like structure, which is so fine that it defied observation with former tools. Careful analysis of the varied and complicated interference phenomena which can be obtained in this way led to the certainty that this internal fine structure of crystals is exactly the same as that

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which atomistic concepts led us to expect; the "illumination" of crystals with X-rays clearly displays their synthesis from atoms and thereby conclusively assures the reality of these atoms.

The wave lengths of X-rays are much shorter than those of ordinary light (X-rays, like light, are also included within the general bounds of the classification of Maxwell-Hertz electromagnetic waves). Because of their short wave lengths it is not possible without further refinement to attain diffraction (interference) of X-rays with the usual, relatively rough optical line gratings. But in crystals nature presented us with "natural diffraction gratings" with which we can study X-ray interference effects. With a very refined device it was possible to obtain diffraction of X-rays with an optical diffraction grating (line grating) so that the wave lengths of X-rays could be measured just as optical wave lengths are. If we know the wave length of an X-ray, from the interference effects which result from the passage of this X-ray through a crystal we can infer the volume relations within the crystal. X-ray interference effects in crystals not only substantiate the reality of atoms with indubitable clearness and distinctness, but also facilitate another determination of the number of atoms in a macroscopic piece of matter—a new determination of Loschmidt's number.

Millikan (in extending and refining older, less lucid ones) performed an experiment which was striking in the simplicity of its fundamental idea. In it he provided tangible proof for the atomic nature of electricity. A mist of minute oil drop-

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lets is sprayed into a chamber; many of these are electrically charged in the process of their production. One droplet is singled out and observed through a microscope. Left to itself it falls vertically downward, due to the force of gravity; not according to the ideal laws of free fall, but rather with constant velocity, since air resistance is proportionately more effective against these small droplets than against larger bodies. If the droplet is subjected to the influence of an electric field, of proper intensity perpendicular to its direction of fall and opposing it, the droplet will start to rise, with a constant velocity, the magnitude of which is dependent upon the field strength. The ratio of the forces working in both cases and the magnitude of the charge carried by the droplet can be calculated from a comparison of the speeds of rising and falling. Consideration of the values obtained for numerous such droplets indicates that the magnitude of the charge does not vary continuously from case to case; none of them ever has a smaller charge than the so-called "elementary charge", and larger values are integral multiples (2, 3, 4 . . .) of this smallest one. Thus we have tangible evidence that electric charges cannot be arbitrarily divided indefinitely; rather, all electric charges are composed of indivisible "elementary charges", each of which carries a charge of 4.77×10^{-10} (4.77 divided by a 1 with 10 zeros after it) electrostatic units.¹

¹ The electrostatic unit of charge (e.s.u.) is that charge which, placed 1 cm away from an equal, like charge (if both charges are considered concentrated in the form of points) exerts upon it a repulsion (force) which will impart to one gram (unit mass) an acceleration of 1 cm per sec² (unit acceleration).

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This atomism of electricity is closely related to the atomism of matter in general. A law concerning electrolysis, discovered by Faraday and named after him, states this relation. Helmholtz had early concluded from this law that if the concept of the atomism of matter were proven correct an atomism of electricity must be assumed. If one zinc and one copper plate are immersed in an aqueous solution of copper sulfate and an electric current is passed through the solution in a positive direction from the zinc to the copper plate, the zinc gradually becomes dissolved in the liquid as further copper is deposited on the copper plate. Quantitatively this experiment shows that when one gram atomic weight of zinc has been dissolved, just one gram atomic weight of copper has been deposited; and corresponding weight relations are found to hold for all similar electrolytic experiments. Moreover, the number of gram atomic weights deposited or dissolved always remains in a simple proportion to the quantity of electric charge which has passed. Thus there occur here regularities of the same character as the laws of weight relations in chemical reactions which Dalton explained by the concept of atomism. In these laws Dalton saw a criterion for the definition and use of the atomic concept; by the same right we can, with Helmholtz, infer the atomistic structure of electricity on the basis of Faraday's law.

Conversely, knowing from Millikan's work that the atomism of electricity not only expresses an auxiliary idea but is a real fact, we can infer from Faraday's law that the atomic structure of matter

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is a reality (which has already been verified in our consideration of crystal interference). The knowledge of the magnitude of the elementary electric charges furnishes one more basis for calculation of Loschmidt's number, characteristic of this atomistic structure of matter.

This in no way exhausts the experiments which show the indubitable reality of atoms. Further direct proofs for atomism are gained in connection with the investigation of radioactivity. From the observation of radioactive preparations it was determined that "alpha-radiation" is simply an emission of electrically charged helium. When this alpha-radiation strikes a suitably prepared zinc sulfide screen, even with limited intensity, it produces a series of small light flashes (scintillations) there. From this effect it is seen that the emitted electrically charged helium is not an arbitrarily divisible, indefinitely diffuse substance, but must consist of discrete particles. By counting the light flashes, it became possible to determine how many single atoms constitute a definite quantity of helium; a new method of determining Loschmidt's number. The results again confirmed those obtained by other methods; this confirmation is evidence that each of these small light flashes actually does come from a single (electrically charged) helium atom.

Of even greater significance was still another process, in which again the effects of single atoms (or "ions", as electrically charged atoms are usually referred to) became visible. A moisture saturated atmosphere is produced in a carefully cleaned, dust-free vessel. If the size of the container is

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suddenly increased by means of a moving piston the saturated atmosphere cools off and becomes "super saturated"—the water vapor begins to condense to liquid droplets. But the first droplets require "condensation nuclei" on which to form, and by removing all very fine particles (dust, etc.) we have eliminated the usual nuclei. If an alpha-radiation from a radioactive preparation strikes the atmosphere of this "Wilson Cloud Chamber", each of the rapidly traveling helium ions produces a fine track, along which are present innumerable atoms or molecules, now likewise electrically charged, which were hit by the alpha particles shooting through the air. Along the entire path these newly produced ions form suitable condensation nuclei; the entire path appears marked as a fine streak of mist visible to the naked eye. Again the effect of a single charged atom—and this time still more beautifully and definitely than by scintillations—has become visible, and again calculations from such "cloud tracks" yield Loschmidt's number.

The Wilson chamber has become one of the most important research tools of modern atomic physicists. Obviously its usefulness is limited to very rapidly flying particles, since only these possess sufficient energy to "ionise" innumerable other atoms or molecules along long paths. But in the processes connected with radioactivity these particles appear under various circumstances; and the Wilson chamber presents a beautiful opportunity to study all the details of the processes associated with their formation and transformation.

Geiger's development, the counting tube, is an

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equally important tool for atomic physics—for determining effects of single, isolated atomic particles. As soon as a single rapidly moving electrically charged atom enters this apparatus a macrophysically perceptible electric charge is produced by an ingenious arrangement. Like the Wilson chamber this apparatus makes it possible to establish the reality of atoms, to determine Loschmidt's number and to study thoroughly atomic physical processes.

5. *Contributions of Atomic Physics.* Before Millikan's determination of the elementary electric charge, electricity—notably through investigations by Lenard—had been represented in pure culture, so to speak, namely in the form of cathode rays formed in a highly evacuated electric discharge tube—also in an X-ray tube, for example, where they produce X-rays by impinging on a solid plate. These cathode rays consist of a flow of negative electricity; from the results of Millikan's experiment it is certain that this electricity must flow in the form of separate, indivisibly small particles. These particles have been named “electrons”; they might also be designated as the atoms of electricity.

The cathode ray which travels rectilinearly when undisturbed can be forced into a curved path through the use of electric and magnetic fields. The motion of an electron deflected under the influence of known electric or magnetic fields must be calculable by Newton's second law—force equals mass times acceleration—if we know the ratio of its charge to its mass, since the acting force is proportional to the charge on a single electron.

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Conversely, this relation of charge to mass can be inferred from the experimental determination of the deflection of cathode rays in electric and magnetic fields.

Since the charge on an electron is known from Millikan's experiment (naturally from the outset it is assumed highly probably that the electrons in a cathode ray possess a single Millikan elementary charge, not two or three; further experiments confirm this as fact) the mass of an electron can be calculated from the measurements on cathode rays. The result shows that the mass of an electron is about 1838 times smaller than that of a hydrogen atom; or, expressed in grams, equals 0.9×10^{-27} (0.9 divided by a 1 with 27 zeros after it) grams.

The method of determining the ratio of charge to mass with cathode rays can also be extended to electrically charged atoms, ions. We know that from hydrogen atoms only one type of ion can be formed—a particle which has almost the same mass as the hydrogen atom itself and possesses exactly one positive elementary charge. Two different forms of ions—each of almost the same mass as the atom—can be formed from the helium atom; one has a single positive elementary charge, the other has two. The impression results that the electrically neutral hydrogen atom contains positive and negative charges within its structure. Obviously hydrogen contains just a single positive and a single negative electric charge; and the negative one must be connected with a proportionally minute mass, whereas almost the entire mass of the

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hydrogen atom is attached to the positive one. The supposition is suggested—and abundant experience raises it to certainty—that the negative charge in the hydrogen atom is just a negative electron. The positive hydrogen ion, from which no further electrons can be separated, is designated as the “nucleus” of the hydrogen atom; it is also referred to as a “proton”. In the helium atom two negative electrons are needed to neutralize the positive charge of the “nucleus”; here again ionization of the atom means simply the removal of one or both electrons. The nucleus of the helium atom is, moreover, identical with the aforementioned alpha particles.

As Rutherford recognized, the structure of all atoms is similar to these. In each atom almost the entire mass is concentrated in a positively charged nucleus; the effect of the “envelope” or “cloud” of negative electrons surrounding this nucleus is to render the atom electrically neutral. Thus the number of these electrons must always be equal to the “nuclear charge number”; i.e., equal to the number of positive elementary charges in the heavy nucleus. Chemists have known for a long time that a very convenient view of the chemical elements can be obtained through their arrangement in the “periodic table of the elements”—wherein the elements are arranged (Meyer and Mendeleef) according to their atomic weights. It was later shown that the atomic weight is not the characteristic by which the various chemical elements are differentiated; many examples today illustrate that atoms of different atomic weights can

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belong to the same element (isotopes) and that atoms of equal atomic weights can belong to different elements (isobars). Not the mass of the nucleus, but its charge really determines the chemical nature of an atom; for the atomic number (nuclear charge number) determines the structure of the electron shells since it dictates how many electrons the neutral atom must possess. Through the structure of the electron shells the chemical properties are determined. Chemical molecules are formed when two or more atoms combine; in the combination the outer rings of electron shells experience certain transformations, but the nuclei remain unchanged.

The size of an atom can be determined in many ways. Their diameters are all equal to about 0.1 millicron. These diameters cannot be specified by exact numbers like the masses can, since the atoms are certainly not smooth spheres with definitely defined surfaces. As in a cloud with blurred boundaries, in an atom only an approximate value can be specified for its diameter. Such values can be determined from crystals, in which the atoms must be packed together very closely. From investigations of gases it is possible to obtain corresponding determinations of these atomic magnitudes. The atomic nuclei are very much smaller; perhaps a hundred thousand times smaller in diameter than the atoms. Thus, almost the entire volume of an atom is occupied by the electron shells. But an electron is essentially no larger than an atomic nucleus. How it is possible that despite this, in a hydrogen atom for example where the entire

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“shell” consists of only one electron, the volume of the entire atom is “filled” up by this electron is a question to which we must return.

While chemical processes involve only the outer electron shells, there are other processes in which the nuclei themselves experience transformation, division or synthesis. In the main these are the already noted processes of radioactivity; but also numerous artificial, arbitrarily produced transmutations have been produced in atomic nuclei in recent years. Thus the nuclei must also be represented as complex structures; today we trace all nuclei back to two building stones, one of which is the already described proton and the other the “neutron”—a particle which has nearly the same mass as a proton but is electrically neutral.

CHAPTER IV

THE PARADOXES OF QUANTUM PHENOMENA

1. *Light Quanta.* It may appear on the basis of the facts described in the last chapter that physical research had almost completely confirmed what had been anticipated beforehand by the Greek philosophers of the materialistic school—even though differences exist in the manner of notation and expression; for example, we do not use the word “atom” today for an indivisible structure, but rather for one which is built up of still smaller parts. We compare, not what we call “atoms”, but electrons, protons and neutrons, with the atoms of the Greeks. But the field of research which appears so clear and obvious through the results treated in the last chapter received unexpected, new complex stimulation from further investigations. There is irony in this development, since the discovery of these new, confusing facts preceded the real proof for the reality of atoms. In 1900 Max Planck made the discovery that directed atomic research along new paths and opened to the theoretical and experimental work of physicists a tremendous new realm for research. Thus the most important developments for atomic physics were crowded together at the turn of the century: and at that time there appeared the criticism, based on Positivism, of atomistic ideas developed until then. First Ernst

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Mach made it clear that in reality the atomistic hypothesis was still completely without proof and totally unnecessary at that time. However, shortly after 1900 the first experimental proofs for the reality of atoms were accomplished. In 1900 Planck had already made the discovery whose real meaning was grasped only a few years ago and from which we gradually realized that atoms are entirely different from what old philosophers thought they were.

The wave theory of light is distinguished from the "corpuscular theory" of light embraced by Newton—whereby light is said to consist of a shower of very fine particles, "corpuscles"—by the proposition that the energy of light is subdivided continuously at pleasure. This proposition appeared to be confirmed by primitive experience, as had that of the unlimited divisibility of matter. In the region of the planet Neptune the same amount of light energy which illuminates one square centimeter on the earth's surface has spread out over a surface of 900 square centimeters; arrived in the vicinity of Sirius this light energy has spread out so far in space that it illuminates about 10,000 square kilometers of surface, yet within the limits of the differentiation ability of the human eye this distribution is still quite uniform, as is seen inversely in the radiation coming to us from Sirius. The sparkle of the fixed stars is due to disturbing effects in the earth's atmosphere; an observer on the moon would see these stars shine with regular brilliancy. The wave theory of light, according to which light

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is propagated continuously through space, maintains that this expansion of light energy can be continued indefinitely.

But there are experimental results which contradict this idea. Let us consider the "photoelectric-effect", the regularities (Lenard, Einstein) of which can be explained briefly as follows: if ultra violet light of sufficiently short wave length impinges on a metal surface, a constant emission of electrons from the illuminated metal takes place. The remarkable thing is that with a decrease in light intensity the number of electrons emitted per second decreases correspondingly but the velocities of the individual electrons remain constant. If the wave theory of light is correct, we must conclude that the electrons torn loose from the metal can possess less energy, the less intense the light is—just as branches are torn off with less force, the weaker the wind blows. But actually, with constant wave length, no more rapid electrons are produced by the strongest light intensities than by the weakest.

This might still be understandable if the single electrons gathered energy from the light waves until they had received a definite amount before shooting out. But then a finite time would have to elapse for very weak light intensity before the emission of the electrons could begin. This is also not the case. Remarkable experiments were performed; a low intensity light source was set up so that it would take hours for a single electron to obtain the amount of energy the emitted electrons actually possess. Even under these con-

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ditions not even the smallest measurable interval of a second elapsed between the beginning of the illumination and the beginning of the electron emission. We do not acknowledge that something completely unintelligible for the wave theory of light has occurred here; yet it appears that Newton was somehow right, and that the incident ultra-violet light is to be compared to a hail shower, its energy being concentrated in innumerable corpuscular particles.

It was also possible to determine the exact law of this concentration of energy from the photo effect. A monochromatic ray of light (which according to the wave theory includes just one wave length) by this theory merely possesses equal "light quanta", each of which contains an amount of energy that is proportional to the wave length; or, otherwise stated, proportional to the frequency (number of light vibrations per second) of vibrations. The ratio of light quantum energy to frequency of vibration is the same for all light quanta; it is designated by the letter h (Planck); this famous quantity which controls all of modern physics—it is called the Planck quantum of action—has the value of 6.6×10^{-27} (6.6 divided by a 1 with 27 zeros after it) erg-seconds and the dimension of "action" (energy times time). Newton of course was not aware of this connection between the energy of light corpuscles and frequency—and he could not have found it, since it is not a statement which fits into a light theory which appears internally incontrovertible, but rather, presents a connection between two different, diamet-

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rically opposed theories of light; the wave theory on one hand and the corpuscular on the other.

The presence of these light quanta in radiation can also be recognized in the radiation itself; not in as tangible, lucid a form but as the result of more profound considerations and experiences. Consider a black walled vacuum vessel; if the walls are held at constant temperature the vessel will be filled up with electromagnetic radiation. For these black walls constantly emit a definite radiation—only heat radiation at lower temperatures, but also visible light at higher temperatures, as is seen in a glowing iron. The radiation constantly emitted by the walls of the vessel is absorbed again upon reaching the bounding wall, but a certain amount of radiation energy will remain present permanently. The problem, upon solution of which Planck discovered his quantum of action, is this: what is the intensity distribution in the radiation (usually called "black body radiation") which fills this hollow volume? What proportions of infra-red, red, yellow, violet, ultra-violet radiation are contained therein and how is their intensity divided among the various wave lengths of the spectrum when this radiation is resolved spectroscopically?

This problem had already been attacked experimentally and theoretically by many investigators before Planck. The theoretical investigation had led to a remarkable obstacle. It had been shown that the "kinetic" theory of heat answered this problem definitely; if the most fundamental principles of physics are correct and the kinetic

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interpretation of heat phenomena is admissible, a definite law must hold for the spectral resolution of black body radiation. This law was called the Rayleigh-Jeans radiation law. Its theoretical derivation depends upon considerations which make it possible to compare the average energies of the different light waves in a black cavity with the average energies of single atoms in gases or solids. The Rayleigh-Jeans law was actually confirmed for the infra-red side of the black body radiation spectrum. (More exactly, these are the facts: the Rayleigh-Jeans radiation law is valid at a fixed temperature of black body radiation—i.e., of the container walls—for a part of the spectrum, from the longest wave lengths down to and including part of the region of shorter wave lengths. The higher the temperature becomes, the further the range of validity of the Rayleigh-Jeans law is extended toward the shorter wave lengths.) From this experimental confirmation of the Rayleigh-Jeans law on the infra-red side of the black body radiation spectrum another possibility was presented for the determination of Loschmidt's number; for from measurements on black body radiation it can be inferred how great the average kinetic energy of the atoms must be at certain temperatures.

Actually, however, the Rayleigh-Jeans law is not absolutely valid; the further we go from the longer toward the shorter wave lengths the less exactly this law is fulfilled. At very short wave lengths the difference becomes serious. The Rayleigh-Jeans law produced an absolutely erron-

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eous result for very short wave lengths; according to it the short wave lengths must possess so much energy that the total black body radiation summed up from very large wave lengths to infinitely small ones becomes infinitely great. If this is to be taken as striking proof for the falseness of the Rayleigh-Jeans law (in relation to short wavelengths), Jeans' expedient—there is no real black body radiation; cavity radiation can only be partially black (with respect to the longer waves)—must be considered. But then the black walls would send radiation energy into the cavity unlimitedly; the energy of the spectral region within which black body radiation is already present would continue to increase with time and more and more radiation would be piled up in the short wave length region. These conclusions contradict our experience and the physical theories which lead to the Rayleigh-Jeans law must necessarily be in error. This is of serious import for physical theory because no special hypotheses had been required for this law, now proven to be false. A revision is necessary in the most primitive, fundamental assumptions and ideas of our physical theory.

Planck, who discovered the true law of black body radiation was forced to new and curious considerations to be able to interpret the law he had formulated.

Essentially his new ideas—although at first he sought to formulate them with as much caution and restraint as possible—meant nothing else than a radical break with the wave theory of light; the

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light quanta produced experimentally by the photo-electric-effect were also necessary on the basis of Planck's observations.

The concept of light quanta solves the difficulties of the Rayleigh-Jeans law quite simply; a constant increase of intensity at the short wave length end of the spectrum is prevented by attributing high energy to the light quanta corresponding to short wave lengths (high vibration frequencies).

Investigation of the Compton effect gave important verification of the light quantum theory. According to the Maxwell theory of light, when a light wave spreads over free, unbound electrons the following must result: the electrons are induced to periodic oscillation through the periodically varying electrical forces of the light waves. In turn, each of these oscillating electrons will then—like a small radio transmitting antenna—emit new electromagnetic radiation in all directions.

This is referred to as a “scattering” of the radiation incident upon the electrons; part of the energy of the primary radiation is deflected from the original direction of propagation and is divided in all directions around the “scattering center”. When this process is investigated experimentally by the use of light with very rich energy quanta (for the effect to be noticeable, X-ray “light” must be used) the results fall beyond the bounds of the electromagnetic wave theory of light and again clearly demonstrate the presence of light quanta. An in-

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crease in wave length of the scattered light is established. (According to the above explained proposition, the scattered radiation should have exactly the same frequency of vibration as the primary radiation since the frequency of the scattered radiation is determined by the frequency of the "antenna", of the electron, and the electron oscillates in the same rhythm as the primary wave exciting it.) In its quantitative regularity the increase in wave length of scattered radiation (discovered by Compton) permits recognition of the physical process which limits it. The validity of the inferences concerning this was later verified by further experiments utilizing the more refined methods of the Wilson cloud chamber, the counting tube, etc. Today we are certain that collisions of light quanta and electrons are the basis for the Compton effect. The single process of this phenomenon appears as follows: a single light quantum impinges against an electron. The electron is displaced in its motion by the collision and the light quantum is deflected from its original direction of flight. The collision proceeds according to the laws of elastic impact; i.e., the total energy of both bodies after impact is the same as before impact; the "center of gravity principle" or the principle "action equals reaction" is also valid.

This latter principle (called the center of gravity principle or the principle of conservation of momentum) is as important for modern physics as the principle of the conservation of energy. Like the energy principle, the momentum principle was first recognized and formulated in mechanics. The de-

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signation "center of gravity principle" stems from the following description of its effect: an acceleration of the common center of gravity of several bodies can never result from mechanical reciprocal action of these bodies; e.g., with all the mutual actions of the sun and planets the center of gravity of the system (which almost, but not exactly, coincides with the center of gravity of the sun) always retains its uniform rectilinear motion relative to the fixed star heaven. Or when a cannon is shot, the same force is exerted on the cannon as on the projectile, but in the opposite direction. From this formulation (equivalent to the other one) there results the expression "action equals reaction". Moreover the relativity theory, the results of which are indispensable for the quantitative understanding of the regularities of the Compton effect, demonstrated that this principle of the conservation of momentum is intimately related to the energy principle.

Thus the collision of light quantum and electron proceeds according to the laws of conservation of momentum and energy. If the direction of flight of a single one of the scattered light quanta is known, the direction of motion of the electron hit by this quantum can be calculated exactly. It has been confirmed experimentally that for each electron struck one light quantum is scattered (Compton-Simon, Bothe-Geiger).

2. *Quantum Transitions.* In the observation of a non-luminous Bunsen flame containing a little sodium vapor (common salt introduced into the flame) through a prism or diffraction grating, the

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spectrum shows only a single line¹—in the yellow; the entire visible portion of the light includes only the one wave length corresponding to this line. Conversely, if light, shown by spectroscopic analysis to contain all visible wavelengths is passed through sodium vapor the only light absorbed is that corresponding to this yellow spectral line; the sodium vapor transmits all other visible light. This famous discovery of Kirchhoff and Bunsen became the foundation of “spectrum analysis”. Like sodium, every other neutral element possesses characteristic spectral lines—in the visible region, however, not a single one like sodium, but usually a large number of lines; e.g., iron has several thousand lines in the visible spectral range alone, and for each element there are additional lines in the infrared and the ultra-violet. Small displacements of spectral lines and resolution of a single line into several closely adjacent ones can be obtained by exposing the light-producing atoms to the influence of electric or magnetic fields (Stark effect, Zeeman effect). But with this exception the spectral lines of each element are rigidly defined; therefore, the elements present in the flame can be determined from the investigation of the spectrum of a flame.

For chemists this has become one of the most important methods of detecting very minute traces of elements.

Light sources in which molecules rather than atoms produce the light have shown that each type of molecule possesses a definite characteristic spectrum.

¹ Actually a pair of lines.

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Spectral analysis became a most important, fruitful aid to astronomy. The spectra of stars and nebulae contain chiefly the same spectral lines which we can produce by introducing different elements into terrestrial light sources. Fundamentally this furnishes proof that the entire stellar world is composed of the same chemical elements we have become familiar with on our earth. Furthermore, investigation of stellar spectra yielded an abundance of knowledge concerning the physical nature of the different heavenly bodies and the conditions to which luminous atoms are exposed therein. Particularly, several lines were found in stellar spectra which—as an exception to the rule—could not be reproduced in any laboratory on the earth and furnished evidence that matter exists there under conditions which cannot be imitated in the laboratory (e.g., gases of absolutely tremendous rarefaction). Even in these cases there appear no chemical elements other than those known from earthly experience. Spectra furnished more refined and more abundant information on the nature of atoms, than any other method of investigation. It seems apparent that there is more to be learned about the nature of the iron atom from the spectrum with its many thousand lines than from the little numerical data concerning mass, atomic number and approximate size of the atom. But first it was necessary to understand the language of these spectra, and that was not at all easy. That inner motions of the atoms were betrayed on the outside through light emission was not surprising in itself; for it is known that the constituents of the atom

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are electrically charged and in motion must act like a small antenna. But it was not possible to interpret the regularities of the spectra through an explanation of the radiation concept based on the principles of classical mechanics and electrodynamics. Careful analysis demonstrated simple and beautiful mathematical regularities in the spectra. The spectral lines of hydrogen, for example, can be represented in wonderfully simple mathematical formulae (Balmer, Lyman, Paschen); and Ritz formulated a quite general mathematical law (named after him) of very simple form for all elements. But it was shown to be impossible to obtain a physical explanation of these empirically determined regularities on the basis of the physical concepts established before 1900, the basic ideas of which we attempted to explain in the preceding chapters. Despite its important contributions to chemistry and astronomy all spectral investigation remained completely outside the theoretical structure of physics of that time. The regularities found by Balmer, Ritz and others, which were not self-explanatory, remained with all of spectroscopy in the museum of physical science.

This condition was altered by the development of the quantum theory from Planck's discovery, first hesitantly and in later years more and more rapidly and forcefully. In 1913 Niels Bohr demonstrated the possibility of explaining the hydrogen spectrum, the simplest of all spectra, on the basis of the quantum theory; and beyond that of understanding the general Ritz principle through this same theory. Since then the extremely rich development of Bohr's

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ideas showed wonderful fruitfulness. With the close reciprocal action of theoretical thought and further experimental research our knowledge of spectra increased to a tremendous extent; simultaneously also the meaning of their obvious regularities gradually became clear. To grasp a few of the principal points of this development it will again be necessary to disregard historical sequence.

The so-called "electronic-impact experiments" of Franck and Hertz led to conclusions as fundamentally surprising as the discovery of light quanta. In these experiments the atoms of a gas or vapor were bombarded with electrons, the velocity of which was controllable and known precisely and it was shown that with very slow electrons the collisions are always strictly elastic.

If any macrophysical system capable of internal oscillation is struck a blow from the outside, the system enters into more or less vigorous oscillation. The energy content which the system removes from the impinging body and absorbs as internal energy can assume all possible values from zero to the total energy of the striking body; a very weak blow from an energy-poor body can only transfer a little energy; but there always remains the possibility of a second, weaker collision wherein a still smaller amount of energy is transferred. In all cases it is "infinitely improbable" that no energy at all is transferred; thus, the collision is exactly "elastic".

The Franck-Hertz experiments show that an atom behaves quite differently in this respect. Electrons of very small velocity can not convey

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internal energy to the atom at all; an atom never takes up such a small amount of energy. The electron must possess a certain minimum amount of energy if the atom is to take up any from it in its internal system and then it removes all this energy from the electron, never only a part of it. If the kinetic energy of the electron is a little greater than this minimum the atom always withdraws from the hitting electron (if at all) only exactly this minimum amount of energy. If the electron has still greater energy the atom can take from it at collision certain (definite) greater quantities of energy.

In the macrophysical system the energy content has a certain value which can vary continuously; but in the atom the energy content is not capable of continuous change. Instead there exist definite "energy levels" for the atom. The meaning of this phrase will become clear directly since we can illustrate the difference between continuously and discontinuously changing energy through comparison of an inclined, smooth path with a staircase. But one must not assume that the energy levels (steps) of an atom follow each other with equal separation. As a matter of fact these separations vary within an atom; and besides, the position of the various energy levels is quite dissimilar in the different elements. Each element possesses an infinite number of such levels, compressed closer and closer together on top to a certain limit; should the atom take up more energy than corresponds to this upper limit of energy levels it must become "ionized"—an electron is torn out

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of its electron shell and flies forth with the surplus energy. This ionization of an atom through the impact of a sufficiently high speed electron had already been discovered for a few cases by Lenard; but for us here the energy levels below the "ionization limit" are far more important.

The paradox of this result is obvious: one can not imagine a fact which smacks in the face more brutally all the concepts on which classical physics is based. The principle of continuity is pierced. Since it is established that an atom can never possess energy levels other than those which correspond exactly to those valid for this atom, we must resolve, consequently, that changes of energy also can no longer follow continuously. Therefore the atom is no longer the same as a macrophysical structure, the energy content of which increases and decreases continuously. A change of state through which an atom shifts from one of its possible energy levels to another one is a discontinuous elementary process, a "quantum transition". Nature makes transitions!

Paradoxical as these conclusions are, they agree harmoniously with the equally paradoxical determinations we were forced to make concerning the nature of light. We have now learned that an atom changes its internal energy in discontinuous jumps. We learned earlier that the energy of a light ray—in sharp distinction to the assertions of classical wave theory—is concentrated in individual light corpuscles. Both paradoxes fit together. We arrive at the conception that light production by atoms proceeds in such a way that an atom in a quan-

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tum transition changes its energy discontinuously and emits the energy that has been freed in the form of a light quantum. The absorption of light is the exactly opposite process. This concept was checked and confirmed in all its inferences by Franck and Hertz (and after them by many other physicists) in an abundance of experimental tests. Through it we can calculate all the spectral lines of an atom from a knowledge of its energy levels; and the converse, since we know that a light quantum of a certain energy (as it results from a quantum transition in an atom corresponding to an energy change of the atom) also possesses a quite definite wave length which can be calculated from the energy according to the above relation. It was also possible to determine directly by experiment that atoms which have been raised to a definite energy level, perhaps by electron impact, emit from the possible spectral lines of the element in question just those for which, according to this concept, the energy level in question is the "initial condition". Energy transfers between two colliding atoms had also been observed; here simultaneously the one atom jumps to a higher, and the other to a lower level. The possible remaining energy surplus is converted into kinetic energy of the separating atoms. These are only quite fleeting hints; but that the above idea gained from the existence of light producing (or light absorbing) processes is correct has become an irrefutable certainty through modern experimental measurements.

3. *Dualism; Waves—Corpuscles.* We inter-

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rupted our consideration of light phenomena before we succeeded in finding a solution of the contradiction between the wave and corpuscular theories of light which were established reliably through experiments and which both represent inescapable results of experiment. But they mutually contradict each other; and instead of a solution of this contradiction we have as yet seen no further than a combination, an arrangement between the two mutually contradictory theories in the form of a relation which permits the proper wave length to be calculated from the energy of a light quantum, or vice versa.

The paradoxes only increase when we realize that this same incomprehensible anomaly also appears in other radiations. We know that cathode rays really consist of a flow of electrons; yet if these cathode rays are passed through crystalline foils, there result interference phenomena analogous to those produced by X-rays. The discovery of these interference effects was so amazing and unexpected in view of our previous certainty of the corpuscular nature of cathode rays that at first it was disregarded by experimental physicists. The wave properties of cathode rays—like the Maxwell-Hertzian waves—were first predicted by theoreticians. It was de Broglie who arrived at the bold idea that the “dualism” of waves and corpuscles with which we became familiar in light could also be found in cathode rays and other material radiation. De Broglie was able to show that if such an effect is actually present the corresponding wavelengths in the cathode ray

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must be defined by very simple theoretical laws (for the detection of which the theory of relativity was again extremely important).

Only several years after de Broglie's theoretical disclosures were these paradoxical suppositions checked experimentally. The result was positive; the interference effects predicted by de Broglie were exhibited for cathode rays. Later these experiments were even performed with corpuscular rays—with a stream of atoms; here the proof of the wave properties is still more difficult because the wave lengths are much shorter than for electrons (cathode rays) of the same velocity. According to de Broglie the wave length corresponding to corpuscles at a certain velocity is inversely proportional to their mass. Today we can no longer doubt that this dualism of waves and corpuscles is a quite general physical regularity; each wave radiation which takes place must simultaneously be a corpuscular ray and each corpuscular ray must on the other hand also exhibit wave properties. Practically it is only for light and the lightest corpuscles that it is possible to grasp both sides of the phenomenon with our present experimental methods. For all other cases the de Broglie mathematical formula yields results for the correspondence of waves and corpuscles which lie beyond the possibilities of practical observation due to their minuteness. This is just what is to be desired; only in the realms of atomic phenomena is there room for dualistic phenomena; it would be a gross contradiction of experience for a theory to maintain that these dual-

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istic phenomena also occur in the macroscopic, that corpuscles are perhaps evident in radio or sound waves or that conversely interference effects resulted when a machine gun was shot against a garden lattice.

The paradox of this dualism requires no emphasis; here we are faced with phenomena which are completely inconsistent with the ability of our classical physical theories for intellectual reproduction. Let us consider a concrete example. In a black, light-impervious screen two very small openings are introduced close to each other. Light from a point source passes through these on to a photographic plate set up some distance away. The intensity distribution of the light striking the photographic plate is recorded on it. For sufficiently small openings (and sufficiently small separation between them) the result is not two light spots on the photographic plate as would be expected from exact rectilinear propagation according to geometric shadow construction; the two light rays which come through the two openings interfere with each other.

There was discussion of the supposition that the intensity distribution on the photographic plate would change if the light intensity were made infinitesimally small—so small perhaps, that on the average only one light quantum would be emitted from the source per second. For it is naturally an obvious expedient to attempt to explain the interference effects as a result of a mutual action of different light quanta upon one another. One would then have to imagine that

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the light quanta which passed through the one opening reacted mutually with those which went through the other opening, the interference resulting from their interaction. But the inevitable consequence that the interference effect must be destroyed for very small light intensities where the light quanta occur individually and can not combine in any way was not confirmed by experience. Regardless of whether the photographic plate is very strongly illuminated through the screen openings for a very short time or whether it is illuminated for a correspondingly longer time with weak intensity exactly the same diffraction pattern is formed on it.

Thus we can not do otherwise than imagine that interference laws apply to the individual light quantum. Naturally a single light quantum emitted by the source can only be absorbed in a single grain of the photographic plate. Intensity distributions which appear continuous to the rough view can therefore occur only if large numbers of light quanta are absorbed. Here we must revert to the concept of probability; we must say that one single light quantum emitted by the source possesses a certain probability that it will appear at the exact position of the plate we are viewing; and this probability is given precisely by the light intensity at the point of the plate in question calculated according to classical wave theory. But how does the light quantum reach there from the light source? Previously we emphasized that a self-evident provision of classical Galileo-Newtonian mechanics lies in the conviction that a

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physical body cannot reach a place from another except by traversing a continuously connected path between these two points. But how can this be reconciled with the interference considered in our example—from which we know explicitly that interference is not only shown for a light quantum, but likewise appears in principle for material particles like electrons and atoms? The answer we must resolve to accept is that this cannot be reconciled and that we must regard this self-evident provision of classical mechanics as a proposition in plain disagreement with atomic and quantum physics. It is only possible to define the path along which a particle moves continuously insofar as interference phenomena are absent; where interference stands out perceptibly the usefulness of this classical concept ceases fundamentally.

As enigmatical as these facts are and as much as they contradict all our thought and visualization habits, it should be understood that in a certain sense the picture of nature is simplified by this dualism. Formerly we believed that there were both wave and corpuscular radiations in nature; and our classical viewpoint let us consider them as completely and irreconcilably different. Now we see that, in reality, nature recognizes only one kind of radiation which could not be imagined on the basis of classical physics, since on the one hand it exhibits properties which correspond to our classical wave representation but on the other hand corresponds to the classical representation of a corpuscular ray.

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We admit that we still have not understood the thing, and make it clear that from these determinations the previously disclosed phenomena become more understandable—"more understandable" in the sense that in any case we recognize connections between them and the paradoxes being discussed now. It has been mentioned that the spatial extent of both the atomic nucleus and the electrons is about a hundred thousand times smaller in diameter than an atom—the hydrogen atom for example. Now we resume consideration of a problem introduced then—how it is possible that the one electron in the hydrogen atom, despite its small size, can "fill up" the relatively enormous space of this atom. According to our present knowledge the electron must also be imagined as a wave and this problem becomes quite different. Now we must imagine that the charge of the electron, in the sense of the de Broglie wave theory, is somehow "smeared" over the entire volume of the atom, so that this single electron actually forms a "cloud" of electrical charge.

There is also a fact connected with the dualism of waves and corpuscles which in a suitable characteristic manner distinguishes the modern quantum theory corpuscular concept from that of the indestructible atom in Greek philosophy. Electrons (and the same holds for all other corpuscles) possess no "individuality".

Two widely separated electrons may approach each other, meet, separate again and return to their original positions. It can never be determined whether "the same" electron has returned

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to that position or an “exchange” of the two has taken place—it must immediately appear senseless, considering the previously described criticism of physical statements, to pose this problem at all, to desire a yes or no answer to it. For fundamentally all criteria are lacking which could lead to a choice between the alternatives. We must imagine all electrons as completely equal; and it is not possible to place an “identification mark” on an electron in any way. Thus far we remain in harmony with classical atomic philosophy. But now, through the dualism of waves and corpuscles, a new idea appears. We are no longer to remain certain of the identity of an electron permanently by observing its motion; when the definition of a path becomes impossible or uncertain through interference effects, two electrons which approach each other very closely can “interchange” so that they can no longer be distinguished individually.

4. *The Limits of Causality.* Consideration of interference phenomena caused a modification of the law of motion of a corpuscular particle traveling free of force. According to Galileo and Newton we said earlier that a body that is not influenced by an external force continues along its path rectilinearly with the velocity it once attained. If this were the case for light quanta, obviously there would be no interference, no diffraction phenomena; light quanta striking a perforated screen would quite simply be partially kept back by the screen and partially transmitted through the openings, and beyond the openings they would

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move on rectilinearly—the simple geometrical laws of shadow construction would hold with unlimited exactness, without being broken down by diffraction phenomena. Instead it was necessary to formulate the law of motion for light quanta emitted by the source which reached the photographic plate through the screen openings so that it included the word "probability". We spoke of the probability that the light quantum in question appears at a certain place on the plate, and formulated the natural law concerning this so that the light intensity calculated according to the wave theory was indicated as an exact measure of this probability. Apart from all other difficulties, this result was in abrupt opposition to classical causality which had attained such clear and convincing form in the Galileo-Newton mechanics.

That we actually do not progress if we adhere to the classical theory of causality is also indicated by various other facts. The radiation which emanates from radium, as the elementary process, is an indication of the disintegration of the radium atom nucleus; emission from the radium nucleus is always in the form of an alpha-particle (helium nucleus) and what remains is the nucleus of another element (radon—radium emanation). But in a large quantity of radium atoms a simultaneous disintegration of all the radium nuclei does not occur; the law prevails that after 1580 years one half of the original amount of radium has remained unchanged; after 1580 more years half of that half remains, and so on. The physicist finds himself here in the same position as the director of

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a life insurance company. Without being able to betray anything to the insured individual about the probable instant of his death, the insurance director can still recognize the statistical law for the average time of death among a large number of insured—and thus can recognize reliably that an insurance business can be established on that basis. Likewise, the physicist knows how many of a thousand million radium atoms, for example, now present will disintegrate within the next year; he does not know whether a single radium atom presented to him will decompose within the next second or will still survive for millions of years. This could simply be considered as the incomplete state of our knowledge; it is possible to believe that physicists of the future will learn to place a prognosis of its life-expectancy on a single radium atom. But the above stated mathematical law for the "dying" of radium atoms contradicts this idea. A simple mathematical consideration shows that this law is equivalent to the following determination: a single radium atom, submitted to us today, has a definite probability of disintegrating within the next 24 hours. If this radium atom actually has not disintegrated by the first of January of the year 3000, the same probability exists then for its decomposition within the next 24 hours as now. The problem of radium atoms is entirely different from that of the human being, who, having nearly reached the age of 100 years, must expect his death within the next month with much greater probability than a 20 year old. It is not a

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peculiarity of living organisms that the probability of death changes in the course of time; it is merely a general result of the theory of causality that we expect the probability for the disintegration of a physical structure due to internal causes to change in the course of time, since it is determined by the previous history of this structure. By contradicting this expectation the radium atoms represent a physical event that is not consistent with our classical conception that each effect can be traced back to a definite cause.

Let us consider still another example that makes it even clearer that this denial of the classical concept of causality is not to be understood as a temporary imperfection of our knowledge, but is inherent in the nature of the thing—again showing how incorrect our previous, classical concepts were. Light waves were previously described as transversely vibrating waves. With the aid of a “Nicol prism” the physicist can resolve a light ray into two component waves which are “linearly polarized”; that means that in each of these component rays the electric field intensity of the light oscillates only within a definite plane determined by the light ray. In the two component rays these “vibration planes” are perpendicular to each other; one component wave is transmitted by the Nicol prism, the other is reflected. If a linearly polarised light ray impinges on a Nicol prism again, it is resolved in general into two new linearly polarised rays, the plane of vibration of which are mutually perpendicular but are inclined to the plane of vibration of the first

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ray. The relation between the intensities of the two component rays after this second resolution depends upon the angle (given by the relative positions of the two Nicol prisms) of this inclination. If we imagine this experiment performed with just a single light quantum we must say that this light quantum has two possibilities—it can be transmitted or reflected through a corresponding rotation of its original plane of vibration; the intensity relation calculated from the wave theory of light must again give the probability of realization of each of the possibilities. If we wish to maintain the concept that somehow it is causally determined in advance which of the two possibilities will be realized for this one light quantum we shall become hopelessly confused. The angle of inclination of the Nicol prism can be a quite arbitrary one; and besides we can arrange an arbitrarily long row of differently inclined Nicol prisms behind each other; it is impossible to determine the hypothesis of which hidden property of the light quantum predetermines causally how the light quantum will behave in each possible case of this kind without contradicting the irrefutably established probability law for transmission or reflection expressed above. Thus we must decide to admit that causal predetermination of the behavior of an individual light quantum near a Nicol prism is not given in nature; nature does not effect the distinction before the occurrence of transmission or reflection.

CHAPTER V

THE QUANTUM THEORY DESCRIPTION OF NATURE

1. *Quantum Mechanics and Wave Mechanics.* We have traversed the realms of physical research as rapid travelers. Since we failed to take along the heavy weapons of mathematics, we have been limited, so to speak, to the role of a civilian war correspondent in the land of physical research who must be content to draw some mood pictures of the events there without seriously pursuing the strategical and technical problems. We passed by rich departments of knowledge, varied and beautiful in their content. To omit consideration of the thought structures in which modern physical thought triumphs over the apparently hopeless paradoxes and difficulties which were evidenced in quantum physical experiments would require still greater decision. It is not possible to relate and explain here the heavy weight of experimental quantitative proof of the content and mathematical laws of modern quantum theory; a clarification of the philosophical-logical character of this theory by intimation must suffice. But even for that the author, who wants to make it more easily accessible to the reader, must request special attention.

Let us consider briefly the historical development of modern quantum theory. The investiga-

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tion of atomic spectra (and the energy levels related to them) presented physical research with an abundance of varied problems, in the step by step clarification of which physicists gradually worked out an understanding of the regularities of quantum physics. Niels Bohr, who started this development in 1913 also remained its leader.

Without going into the thousand different problems of this field we shall consider the Bohr "correspondence principle". Although it was mentioned in reference to the energy or relativity principle—and not opposing these in its meaning—the correspondence principle has a quite different character from the energy and relativity principles. These latter are natural laws in finished, perfected form; their content can be expressed clearly and thoroughly in a few words. But the correspondence principle presents peculiar difficulties to the intelligence since its general content can only be described by intimation, or it can be illustrated in special individual examples. For the correspondence principle is not a finished, clearly definable law of nature, but indicates the direction in which Bohr's conviction about the solution of the quantum puzzle was to be sought, and in which he wished to steer the reflection of the quantum investigators. It only becomes clear in the history of quantum theory that not only individual great discoveries are decisive for the development of our knowledge but that under certain circumstances the change of our spiritual attitude toward problems can be much more important. Physical thought develops not only from

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combining the compilations of results of individual observations and their logically-exact treatment; but rather the attainment of decisive new intelligence depends essentially on a creative phantasy, which for its part depends essentially on spiritual hypotheses and on the attitude our intuition assumes toward these things. Bohr's historical contribution lies not only in the individual, pioneer discoveries through which he enriched quantum theory but also in the penetrating force his spirit exerted for the creation of a new spiritual "atmosphere"—wherein the problems were first gradually elucidated as the essential became distinguishable from the unessential and effective control of the solution became possible.

The meaning of the correspondence principle is not purely historical; it is still indispensable today in the sense that it teaches us to view modern quantum theory knowledge with the proper attitude.

The differences between quantum theory and classical physics are so deeply rooted that many physicists were tempted to regard the ideas of classical physics as absolutely useless for the comprehension of atomic physics; they attempted to introduce arbitrarily invented, new, untraditional ideas. But Bohr had—and this is the content of the correspondence principle—energetically pointed out that in all individual problems a verifiable close similarity exists between classical and quantum theory despite their fundamental difference. The following is a rough example: classical physics predicts that atoms, which con-

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sist of electrically charged particles, necessarily emit light in the execution of internal motions. This prediction is correct. The elementary processes of this light emission do proceed quite differently from macroscopic antennae; but the fact remains that the fundamental expectation is fulfilled. That is an example of the close relationship which exists between classical and quantum theory despite their incisive difference. There are other examples of this relationship, much finer examples; and through Bohr we gradually learned to see that such kindred relationships can absolutely be uncovered for each concrete individual problem through more exact analysis.

In his emphasis on the affinity of classical and quantum theory there exists, however, a decided prominence of the independence of the quantum theory from classical theory. Since we learn to "understand" various quantum-physical individual problems better through uncovering kindred relationships "in the manner of correspondence", we gradually attain one of the concepts of quantum physics used in classical theory but separated from it by fundamental differences and independent in itself. Such a discovery is a radical challenge to the repeated spasmodic attempts throughout the course of historical development to somehow want to "explain" the characteristic quantum phenomena—to want to reduce them to ideas which conform more closely to the classical.

With the progress of this development it gradually became clear which problems in general should be answered by a logically effected quantum

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theory. Here the positivist consideration must be repeated very forcefully; the goal of a purely intellectual comprehension of quantum phenomena must be a description of the experimental facts themselves. The experimental facts involved here are collectively of the following sort: a specific atom, characterized by its atomic number, according to experience possesses quite definite energy levels. The first problem appears; how can the positions of all these energy levels (for any atom, and likewise for molecules) be determined and calculated from general theoretical principles? Furthermore, we find "transition-probabilities" for these atoms. When an atom exists in an energy-rich condition, after some time it will undergo a quantum transition which brings it down to a lower energy level while the energy freed thereby comes off as a light quantum. The atom has a range of various such possibilities since there are different lower energy levels at its disposal. As in the case of the radium atom described above, it is not possible to predict in an individual case when and where the atom will jump. But experience indicates the existence of quite definite probabilities for the various possible processes. If the atom is irradiated with light there results a definite probability for a quantum transition associated with the absorption of a light quantum. If an electron of a certain (sufficiently high) velocity impinges on an atom, the atom can, as we already know, thus also be induced to a quantum transition. If, furthermore, the atom collides with another atom (of

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the same or a different kind) an energy change can occur, as was already mentioned, in the form of a simultaneous mutual quantum transition.

Definite probabilities prevail for all these processes; based on experience they are always stated in the same ways through the conditions of the experiment in question. They are summarized under the designation of "transition probabilities". Now the problem (besides the theoretical determination of energy levels) that a complete quantum theory must solve quite comprehensively is simply the theoretical determination of the transition probabilities.

In this sense Heisenberg undertook the creation of a "quantum mechanics". He relied upon the success then already achieved in the detailed execution of Bohr's correspondence principle; in fact, the systematic evaluation of Heisenberg's extensions (Heisenberg, Born, Dirac, Jordan) yielded a solution of the problem formulated according to the correspondence principle which was complete in principle. Of course the mathematical formulation of this solution was such that it differed extensively from the mathematically precise renditions of our classical physical conceptions. But this mathematical form of the new quantum mechanics was most exactly suited to the problem (as we stated it) of the determination of transition probabilities. Besides, this new quantum mechanics expressed wonderfully the two-sided relation of quantum to classical theory; namely, fundamental difference on the one side and close connection on the other. The mathematical medium

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of representation utilized is the so-called matrix theory—a chapter of mathematics that had already been cultivated for a long time by mathematicians for its own sake without their surmising the importance it was to attain for atomic physics.

These investigations had just reached a preliminary rounding-off point when Schrödinger arrived at the same goal by an entirely different method. Schrödinger started with de Broglie's investigations. After de Broglie had shown how the uniform rectilinear motion of a corpuscular particle was reinterpreted in the wave theory, Schrödinger wondered how these de Broglie considerations developed for motions influenced by external forces. For this reason he investigated the motion of an electron under the influence of the attraction of a positive heavy nucleus; and thus he arrived at the quantitative description of the electron charge cloud in the hydrogen atom.

Schrödinger could now show that with the solution of the mathematical problem he formulated he had simultaneously also achieved the solution for the apparently quite different mathematical problem which was expressed by quantum mechanics in the form of matrix theory. Thus, when a problem has been solved by means of Schrödinger's "wave mechanics" a mathematical conversion yields the "quantum mechanics" solution for this same problem. This mathematical connection between the two theories, leading to the same result, which in view of the complete difference of the two methods must appear very surprising at first, also supplied the certain basis

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for the physical-abstract interpretation of Schrödinger waves. At first it might appear that the discovery of wave mechanics yielded a mitigation of the contrast between quantum and classical theory; for here instead of the unclassical concepts of transition probabilities, etc., we deal with waves—something closer to classical ideas. But what we just learned with respect to light is still true; the classical wave theory is not the final word. Wave mechanics does not in any way signify for atomic physics the removal or mitigation of the fundamental unclassical characteristics of quantum physics. Also, for atoms with more than one electron (thus for all atoms except hydrogen) Schrödinger wave mechanics assumes a very abstract form; in these cases Schrödinger waves are no longer waves in customary three-dimensional space but are simply a mathematical construction which mathematicians can “illustrate” to themselves as waves in space of more than three dimensions. This abstract, multi-dimensional space can be avoided through another (mathematically equivalent) method of representation, the construction of which was a special hobby of the author's. In this method of representation (“second quantization”), which clings especially closely to the fundamental dualism of waves and corpuscles, the waves dealt with are spread out in ordinary three-dimensional space, but can only be described by means of the ideas of quantum mechanics.

These theories, whose abstract nature will not remain hidden from the reader in even this fleet-

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ing explanation, made possible a number of special uses for individual problems of atomic physics. The precise correctness of the new theory was confirmed without exception in a tremendous field of experimental results. No end is in sight for the further elaboration of special problems on the basis of these principles. The fundamental result may be stated as follows: today we can understand all phenomena which occur near and in the electron shells. Thus all the elementary processes that are the basis for spectral or chemical processes are defined as clearly as the motions of the planetary systems have been since Newton. The only partially explored realm at present remains the physics of internal events in atomic nuclei.

For us it is only important to understand the philosophical nuclei of these new ideas. We again owe special thanks to Bohr and Heisenberg for the philosophical-epistemological explanation of the meaning and significance of the new theories. This became possible through the earlier thorough mathematical understanding of the quantum laws in the so-called "statistical transformation theory" (Dirac, Jordan).

2. *Objectivity.* We return once again to classical theory to emphasize still more clearly the characteristic features through which it differs from quantum theory. We can state three basic principles which should be considered as the most important characteristics of classical theory with the catchwords continuity, causality, objectivity.

We spoke amply of continuity; and we learned

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that just this principle of continuity constitutes a difference between classical and quantum theory. But now we want to make it clear that continuity is not only something familiar to us, but is really an essential, the omission of which is followed with logical necessity by further fundamental deviations from classical ideas.

The assumed continuity of natural processes is essential for our method of executing and evaluating physical measurements. Every measurement we perform is inexact. The physicist considers the "limit of error" for each measurement; for every measured numerical value he records two numbers, the difference between them corresponding to the uncertainty of the measurement. That it is nevertheless possible to draw certain conclusions from an inexact measurement—conclusions, of course, that are also affected by an uncertainty but in any case are rich in content and very definite—is only because the principle of continuity is actually fulfilled in the macrophysical world; trivial changes in the cause are followed by trivial changes in the effect. Consequently an inexact knowledge of causes is still sufficient for an inexact prediction of the effects, although the absolutely certain prediction of the effects becomes possible only with a mathematically more precise (practically unattainable) measurement of the causes.

Uncertainty in the process of measurement deserves a still more detailed investigation. The essential point for us here will become clear if we visualize, for example, the measurement of

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the temperature of a macrophysical body. We bring the body in contact with a thermometer; the thermometer assumes the same temperature as the body in question; and we read off the value. But to be exact, it is necessary to consider that since the body under investigation imparts some of its heat to the thermometer the body itself is influenced and its original condition is altered somewhat. To avoid resultant false measurements the thermometer selected must be much smaller than the body being investigated. (Of course it is possible, if the thermometer used was not sufficiently small, to compute or estimate the temperature change which took place and correct the result for it; but that is a problem in technical method which has no connection with the nature of the thing.) It is analogous for every physical measurement: I must always select such fine instruments for a measurement that in the measuring process the body under investigation itself will not be influenced appreciably by too rough a measuring instrument (such influence would falsify the measured result). Fundamentally a reaction of the measuring instrument on the object being investigated is inherent in every physical measurement; yet in the investigation of macrophysical objects this reaction can be made sufficiently small by the selection of quite fine instruments.¹

This idealization of the process of measuring

¹ This concept of the "fineness" of a measuring instrument should not be understood too vaguely; not the spatial largeness or smallness of the instrument but rather the magnitude of the energy of reciprocal action between the instrument and the observed object is decisive.

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in classical physics depends essentially on the assumption of continuity of all natural processes in the sense that our fundamental considerations are established as though precise measurements were possible for us. It is a "permissible idealization" to base our considerations on this concept of absolute observational accuracy and to interpret the actual inaccuracy of each measurement as an only practically and not principally significant secondary disturbance. This idea cannot lead us to errors, because by classical concepts we can approach ideal measurement unlimitedly, although we can never attain it.

We here consider something which we shall indicate with the word objectivity and which is so characteristic of our general classical-physical thinking that we usually disregard it. We are accustomed to regarding physical observation results as clearly understood according to their importance if we have explained them as effects of an objective physical process or condition. This formulation hides within it a higher type of positivist modesty; a deeper "explanation" of natural processes is relinquished herein for everything. But what is left after this renunciation of all classical-physical theories as a basis for their methods of representation is just this idea in objective events. Perhaps we do not describe planetary motions by specifying when and where or through what telescope the various planets were observed; but we do describe planetary motions as a spatial-temporal process taking place independently of human observation. Naturally one can pursue the familiar

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philosophical considerations which emphasize that without subjects doing the observing there can be no talk of objective matters. But these thought processes are not acceptable to the physicist. To him the motion of the planet Neptune in its orbit is an objective event which was already in process before anyone had seen this planet in a telescope and which continues uninfluenced, independent of whether or when or how often it is observed or photographed. Exactly the same self-evident superposition of objective events is the basis for Maxwellian electrodynamics; we interpret electrical measurement data as indication of an objective physical event in the electromagnetic field which is present in space.

Positivist criticism must remind us that this objectivity of physical events is not a purely logical self-evident fact. For positivism teaches us to view true physical reality only in the totality of experimental results. It is very remarkable and astonishing that in the domain of validity of macrophysics we are in a position to so formulate our summarizing description of experimental results that they are no longer referred to directly but are, so to speak, only minor appendages of the picture we have traced out—a picture which maintains the existence of objective events which occur independently of how and where the observations necessary for their detection are taken.

After what has been said it is obvious that the idea of ideal measurements (made possible by the continuity of macrophysical processes) which do not disturb the observed event in the least is in-

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dispensable for this construction of an objective physical world. Another assumption indispensable for this objectivity is that of complete causality in the macrophysical world. For if we had had to reckon with the occurrences of effects not determined strictly causally we could never have been certain in our observation processes whether the source of an effect we saw was to be sought in the object we were observing or just in a cause-free reaction of our observation instrument.

Thus objectivity would be disturbed if complete causality did not exist; conversely, the representation of objective physical events is a necessary assumption for the carrying through of the idea of strict causality.

That complete causality is an indispensable assumption for the possibility of effecting the representation of objective physical events was already clearly recognized by Kant. But there is no justification for concluding from this insight that the complete validity of the principle of causality throughout nature is guaranteed from the outset independently of experimental experience. All that must be established is this—objectivity also is weakened with the renunciation of complete causality. This is actually the case in atomic physics; we have seen that the principle of continuity can not be given up without objectivity ceasing. And we have learned that continuity ends in atomic and quantum physics. We can consider the appearance of discontinuities in elementary physical processes as the fundamental proposition of modern quantum physics; the atomistic structure of matter may be in-

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terpreted as one facet of this elementary physical discontinuity which also appears in many other forms.

The above examples have already made it clear that in quantum physics a complete causality, of the type we are accustomed to, no longer exists. But we still want to refer particularly to the difference that exists between the quantum theory use of the probability concept and the Boltzmann evaluation of it (for the kinetic explanation of heat processes). In Boltzmann's considerations statistics was a secondary thing; at that time there was no reason to doubt that the motion of each individual atom could fundamentally be calculated precisely in advance. The pursuit of such fine processes was voluntarily relinquished and statistical considerations were used as an expression of an incomplete (but sufficient for the result desired) observation of the events. Whereas in quantum theory the primary natural laws themselves take the form of probability expressions in this case the statistical concepts are not an expression of the incompleteness of our insight into events, but rather an expression of an indefiniteness existing in nature itself. Nature herself did not determine individual atomic processes in advance; from case to case she executes unpredictable decisions which show fixed regularities only in the statistical average. But these unpredictable decisions of nature are always connected with elementary quantum physics discontinuities. Indeed it is the independent cases of quantum transitions that are not predetermined.

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Our earlier example of the interference of light for the screen with two openings already demonstrated that quantum physics must also relinquish the idea of objective events.

With characteristic positivist modesty we limited our problem to the problem of how great the probability is that the light quantum in question will be absorbed in a certain point of the photographic plate. Thus two quantum transitions—and that is typical of the whole modern quantum theory—are placed in a static relation with each other. We observe the quantum transformation of the light emission from the point source; then we observe the quantum transformation of the absorption of the light quantum in a certain grain of the plate; and we can theoretically calculate in advance the probability of the occurrence of the second elementary act after the incidence of the first. But we cannot extend the picture of an objective event between both processes in the form of the specification of a continuous path which the light quantum must traverse from the first position to the second.

Formerly one might have been inclined to suspect that the principle of the objectivity of physical events was also inseparably connected with the possibility of the quantitative, mathematical comprehension of natural regularities. But we see that that is plainly incorrect; everything we try to explain here in words can be expressed in as mathematically clear a form as Galileo-Newton mechanics. We must replace the precalculation of future events on the basis of complete causality possible in the macrophysical domain by a purely proba-

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bility prediction. The probabilities of quantum physics processes are themselves determined exactly quantitatively; in the last analysis they are subject to precise mathematical laws of great simplicity and of the most comprehensive validity.

Despite that, the Kantian interpretation, that complete causality (as well as objectivity and continuity) of natural processes is an indispensable provision of every physical thought in general, is still correct in the following sense: quantum physics experiments are also always performed with macrophysical apparatus. We need macrophysical (thus functioning according to strict causality) apparatus to be able to make any correct observations at all and to be able to determine regularities in the atomic world. Classical physics remains the indispensable support from which an advance into the world of quanta and atoms becomes possible. This can not be altered by the fact that macrophysical laws can naturally be interpreted as results of quantum physics elementary laws. The laws which govern the motions of macrophysical bodies must naturally result from the laws to which their individual atoms are subject. There is no difficulty involved in the necessity of interpreting the strict causality of macrophysical events as a result of the purely statistical laws for the elementary processes. For that is the essence of conformity to statistical laws—despite the incalculability of the separate event, an exact, predictable result occurs in the total effect of a large number of individual processes. The fact that we thus interpret the laws of atomic physics as the really true natural laws

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from which macrophysical laws are derived as results does not permit us to overlook the other fact, that the elementary laws of atomic physics include a tangible content only when they are attached to the frame of macrophysics by concrete application. Herein lies in the final analysis the root of the not only historical, but contemporary significance of the Bohr correspondence principle. For this teaches us to understand the meaning and content of quantum physics laws from their relation to macrophysics.

3. *Complementarity.* Experimental evidence has shown us in a most comprehensive way and with a variety exceeding all expectations the atomistic structure of all physical substrata; not only matter, but also light (despite its wave nature which it exhibits "on the other side") has a corpuscular make-up.

This evidence drives us to remarkable conclusions. How can one observe and investigate individual atoms? We saw that modern experimental technique permits the very satisfactory performance of experiments immediately involved with individual atoms (and therewith to exactly prove the reality of these atoms, without a doubt). Naturally experimental manipulation of individual atoms remains much more difficult and far different from the investigation and measuring of macrophysical, visibly large bodies which are made up of innumerable atoms. For macrophysical bodies we have scales and other mechanical, optical or electrical measuring instruments at our disposal; but there is a decisive difference for measurements on atoms.

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We know that every physical substratum, therefore every physical measuring instrument, is composed of atoms—be they material atoms or electrons or light quanta. This destroys all possibilities of using convenient measuring instruments for this research as is done for macrophysical objects or events.

We have already considered how fundamental for our classical physical ideas and methods of perception is the fact that in macrophysical investigations the back-coupling, the influencing of the object by the observation process, can be made negligibly small through the use of sufficiently fine measuring instruments. But if we consider that all measuring instruments themselves consist of atoms (thus can never be made finer and smaller than single atoms) we see that this method of eliminating the reaction of the measuring instrument is barred when the object to be investigated is itself an individual atom (or a structure containing just a few atoms). There is no longer any possibility of investigating and observing with instruments that are finer than the object in question. Nor is it possible to control the influencing of the object by the measuring instrument and to eliminate it from the result by a corresponding conversion. Thus it must be considered as part of the bargain that fundamentally measurements on atomic objects are always "falsified" in the sense that according to natural law the object experiences a variable interference from the execution of the observation process. Similarly when we try to observe and psychologi-

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cally control our own thought processes we are successful up to a certain degree; but the functioning of the observation itself again influences the observed "object"—our own thought process—and with this sets the limits for the possibility of observation. (One can not, e.g., watch through psychological self-observation how one falls asleep, because just that attention of observing prevents one from falling asleep. Also, e.g., the origin of voluntary decisions is disturbed and changed by internal-controlling self-observation.) Similarities are also found in atomic physics—the observed object is influenced by the observation process itself. With Niels Bohr we can say, the separation between observed object and observing subject begins to vanish here.

It is not at all proper to call this influencing of the object by the process of observation a "falsification". For we are not dealing with a disturbing influence which is in any way limited for the present by the current deficiency of our observation technique; these barriers to the possibility of an ideal observation which does not influence the object itself are limited—through the atomistic structure of physical foundations—by natural law. Therefore, we must ascribe to the atomic objects themselves a certain character of "indeterminateness", of "indefiniteness" of their physical behavior which makes the construction of an objective picture of atomic physical events impossible.

This need not imply that every possibility of exact measurement on atomic objects is doomed to

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failure. It is possible throughout to make each physical property of an atom the object of precise measurements. If a certain property of an atom is observed exactly there result from the observation process (due to the reaction of the measuring instrument to the object) strong uncontrollable and undefined changes (strong "uncertainties") with regard to other properties of this atom. By optionally transferring the interference which is necessarily associated with observation of the atom to different properties of the object it is possible to make accurate observations on the properties of the atom undisturbed by the particular reaction. With this "complementarity", as Bohr named it, the new theory can eliminate those apparently hopeless contradictions we first encountered in the dualism of waves and corpuscles and which we met at every step in quantum physics.

This idea of complementarity must be viewed as the most significant result for philosophy that crystallized out of modern physics. It presents an absolutely new scientific way of thinking which is fundamentally different from classical scientific thinking in terms of objectivized representations. After the intellectual penetration and comprehension of atomic physical phenomena completely inaccessible to the previous method of representation became possible through it, it appears justified to believe that it may further become of epoch-making importance in other realms of natural science. The enlightening force of this idea in solving an apparently insoluble puzzle and contradiction is clearly demonstrated in the famous problem of the dual-

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istic nature of light. The properties connected with the wave nature of light on the one hand and those connected with its corpuscular nature on the other are "complementary" to each other in the sense that they can never appear in one and the same experiment at the same time (and thus come into actual direct opposition). Experiments which let the wave side of light emerge clearly force (through the action that is connected with every experiment) the corpuscular nature of light back into the indeterminate and unobservable; other experiments, which force the corpuscular side of light into prominence, leave undefined and indiscernible all the properties which usually betray to us the wave nature of light. With this wonderful device of complementarity nature combines in one and the same physical object properties and regularities that contradict each other so that they could never exist directly at the same time.

Let us pursue this in somewhat more detail in the already repeatedly discussed example of the interference of light rays transmitted through two screen openings. If we want to let the interference of these two light rays take place to illustrate the wave nature of light we must, as already indicated, relinquish the desire to determine simultaneously through which of the two openings a definite light quantum was transmitted. We can also consider this event from the "complementary" opposite side. We can undertake to desire to observe through which opening the light quantum was transmitted. But then we must conversely relinquish any desire to obtain an interference of the

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two rays. For with the latter intention the only procedure we can follow is to roughly close up one of the screen openings in order to be certain that a transmitted light quantum could actually only have passed through the other opening. There is no experimental possibility of assuring ourselves in any way through which of the openings the light quantum was transmitted without simultaneously so altering the conditions of the experiment that the interference of the two rays is hindered.

As another example let us consider the charge cloud of the electron in the hydrogen atom. If we fix the position of a definite point with a microscope we must assume an inaccuracy which is at least of the order of magnitude of the wave lengths of visible light—thus much larger than an atom. But nothing hinders our imagining that we have a microscope that is not dependent on visible light, but on X-rays or even rays of much shorter wave length (gamma rays). With this microscope we could accomplish measurements of position on an electron with such great accuracy that positions inside of the charge cloud of the hydrogen atom would also be distinguished. Now let us place a hydrogen atom under this gamma-microscope and “examine” the inner structure of this atom so that we determine the position of the electron. In the description of this imaginary experiment we must not forget one thing; namely, that the energy of the “gamma-light” necessary to illuminate and render the electron visible is concentrated in individual light

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quanta which possess very high energy because of the minuteness of their wave lengths. The procedure of the "examination" of the electron in the hydrogen atom is as follows: a single energy-rich light quantum meets the electron, and reflected by it approaches us through the microscope, showing us the exact position of the electron. But in this process the electron experiences a terrific effect; it is thoroughly dislodged from its former condition by the interaction with the energy-rich light quantum and in most cases we can expect that the electron is completely torn away from the hydrogen nucleus; the atom, thus, is ionised.

We can now explain in a concrete way the meaning of the "charge cloud" around the atomic nucleus calculated according to wave mechanics. We repeat the above described experiment innumerable times; and, it must be emphasized, each time we use a hydrogen atom which is in its lowest energy state (normal state). If, instead, we took atoms in a fixed, higher energy level we would have to reckon with a different structure of the charge cloud; for each of the different energy levels, according to quantum theory, there exists a certain specific structure of the charge cloud. By repeatedly measuring the position of the electron in a hydrogen atom in its normal state we find the electron in different positions from case to case, just as in our interference experiment we found the individual light quanta in different places on the photographic plate, statistically distributed according to the light intensity calculated by the wave theory. The statistical distribution

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of the individually measured electron positions is given by the charge cloud calculated according to wave mechanics. It was only with this determination that the concept of this charge cloud attained a clear meaning which is defined by concrete, demonstrable experiments.

At the same time we see in this experiment how the changing actions in quantum physical observation are bound up with the observed facts. Before the act of observation in question the hydrogen atom possesses a definite energy, but in general in these circumstances a definite position of the electron does not exist—the position of the electron is undefined, or only indefinitely defined in the structure of the statistical charge cloud. It is only through the process of observing its location in the gamma-ray microscope that we force the electron to assume a definite position. Notice, we do not prescribe in which position it should emerge; but we do force it into some definite position and thereby force it to a new crisis; now the electron assumes a definite position but simultaneously an indefinite energy exchange has taken place between the gamma light quantum and the electron and the original condition of a defined energy of the atom has been disturbed.

A quite analogous process is represented by the previously described impinging of a linearly polarized light quantum against a Nicol prism. In this case we can also say that the execution of an act of observation has forced the light quantum to assume a clearly defined situation, when previously

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this was indefinite. The light quantum must decide whether to be transmitted by the Nicol prism which has been placed inclined to the original plane of vibration of the light quantum or to be reflected by it. That is a decision of the same kind as that of assuming a definite position forced upon the electron in the above experiment.

It is obvious that there is no more place among these ideas for a complete causality, clearly pre-determining each occurrence. If in a macro-physical structure, the planetary system, for example, we want to pre-calculate future movements exactly we must know two things. First, we must know that the Newtonian law is valid (and not any other one), and we must know the magnitudes of the different planets which are determinative for Newtonian gravitational attraction and for the relations of force and acceleration. Secondly, for any one point in time we must know the positions and velocities the different planets possess at exactly this point in time. Thereby the general course of motion is mathematically precisely determined for all later (besides, also earlier) times. In an electron, however, we are not able to simultaneously determine its position and velocity at a definite point in time. Since position and velocity are complementary, the position measurement in the gamma-microscope makes the velocity of the electron unobservable—and the converse also holds. After knowing that the physical properties of an atom are partially complementary to one another, that therefore it is impossible to

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observe the atom simultaneously "from all sides" as it were (as is possible in macrophysical bodies), it must be regarded as quite natural that pre-calculations of the future conduct of atoms, electrons and light quanta are not possible analogously as in the planets. Let us emphasize once again: this impossibility not only depends on a practical technical incompleteness of our instruments, but depends on nature itself. It is a positive result of the natural laws which in quantum or wave mechanics have attained a formulation which is mathematically exact and is verified by innumerable experiments.

As we saw, we can quite clearly recognize the real root of this impossibility in the basic fact of the atomistic structure of all physical foundation. The indefiniteness inherent in the physical condition of all atomic objects stipulates a corresponding indefiniteness in the process of the action; pre-calculation according to exact causal laws is lacking here. The inability of the physicist to predict for an individual case which of the various possibilities will be realized in the quantum transition which is the basis for an observation process is not due to human imperfection of knowledge; nature herself has reserved until the last the decision for each individual case.

Finally, let us make it clear that our repeated use of the word "indefiniteness" in relation to atomic physical events actually expresses nothing but the impossibility of using familiar classical concepts in the place in question. The impos-

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sibility of describing the relations in objectivised-process pictures lends as many difficulties to the verbal expression as does the problem of a clear representation.

CHAPTER VI

PHYSICS AND WORLD OBSERVATION

1. *Natural Scientists and Philosophers.* It is natural that in the classification of the trends of physical science, after they have been described, the personal opinions of the author play a greater part than they did in the brief summary of the facts. It is desired that the reader recognize the limitations imposed by this.

What has been developed in the preceding are the modern, generally accepted conceptions of the contributors to modern quantum and wave mechanics which were derived from the experimental work in this field. It should be emphasized that some physicists (Planck, v. Laue, also Einstein) consider these thoughts paths too revolutionary and do not accept them as conclusive but still cherish the hope that further development will lead to a certain "restoration" of the older method of representation through new experimental discoveries. But, in any case, these opinions are purely personal and are based on uncertain future hopes which find no support in the present state of our knowledge. The author, therefore, is convinced that the new conceptions must be considered conclusive—new discoveries will at most result in a more radical formation of the revolutionary tendency. Because of the force with which the new concepts follow from the modern state of experimental knowledge and its theoretical

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penetration it follows that the development of these ideas does not belong to one person alone. Its progressive clarification resulted with inescapable necessity for us quantum physicists. I believe that the views of Bohr and Heisenberg, to whom the principal credit for the development of these ideas is due, correspond closely with the presentation given above.

In the following effort—to indicate the attitude of the new physics to more general questions—it shall be our endeavor to limit ourselves to what can be regarded as firmly and reliably established. It shall be important for us in this effort to consider in what direction and how far the results obtained by the new physics contributed to the world problems affecting our times. We shall ignore all problems to which the answers do not appear necessarily predesigned by these bases—also any questions regarding which the author's personal opinion is very definite.

It is likely that this report has clearly indicated that recently physicists were urgently directed to the necessity of an epistemological philosophical proof and contemplation of its function. One would expect, therefore, that the relation between physical and philosophical research would have been especially close and strong; a more complete explanation of why this was not the case at all is certainly deserved. The fact is that from the philosophical point of view the new physics is frequently regarded with scepticism or is challenged. The philosophical criticism is limited mostly to the alleged impossibility of the new thought

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paths and is based on the dogmatic designation of the older concepts as the only possible and invariably necessary ones. This is connected with the wide separation of the paths of the physicist and the philosopher. In Aristotle's time all branches of natural science were still branches of philosophy; but the further development which led to the progressive independence of the natural sciences separated philosophers more and more from natural scientific investigation. The fact that most present philosophical study (quite different than it was for Aristotle) is primarily based on philological-historical studies and depends but little on contemporary mathematical and scientific work¹ cannot contribute to promoting fruitful relations between philosophical studies and scientific research. The developments of modern science make it more and more problematical what subject realms of philosophical research, in general, could provide something of importance to the natural investigator. All the problems amenable to philosophical research in spiritual-scientific spheres—perhaps also in cultural, historical, sociological and allied research—lie beyond the bounds of a natural scientific utilization of philosophy. In our momentary consideration, that type of philosophy which, in general, cannot be interpreted as a part of science, but whose character should be denoted by the word "wisdom" is avoided—Nietzsche imagined such a philosophy, existing outside the framework of scientific thought and ac-

¹ The philosopher A. Wenzl, e.g., is a noteworthy exception; but we cannot go further into his interesting explanations of the new physics here.

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cordingly to be evaluated by quite different rules.

But what problems of specifically philosophical nature are related to natural scientific research? The increasing independence of natural scientific branches from philosophy from Aristotle's time to the present has simultaneously also emptied philosophy of its original content and problems. Up to our time the opinion has remained that it is the task of philosophy to clarify certain "final" and most general questions of natural science; questions which concern perhaps the "existence" of matter, or the "existence" of time and space, or the "existence" of force, or the "final" bases of "existence". The development of physics, however, shows clearly that no useful suggestions for natural investigators are to be anticipated from such endeavor. With the possible exception of attempts to investigate the results and thought processes of natural science with regard to their relation to spiritual or non-scientific problems the only possible modern philosophical work which will be useful and fruitful for natural investigators must concern the theory of the method of natural scientific thought—for example, the questions of the theory of knowledge. The present status of these problems indicates that their fruitful treatment can succeed only in closest contact with the foremost front of natural scientific investigation; the extensive research devoted to the theory of knowledge from the philosophical point of view for the most part stands too far from modern natural science and its actual problems.

Because of this condition physicists were led

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to reflect upon the most profound questions of physical knowledge in their own way; and from experimental evidence, which no one could anticipate a few decades ago, they were led to develop answers, the inescapability of which can only be exactly understood on the basis of more certain, superior knowledge of these experiments.

We have shown in previous chapters that the philosophical concepts developed by the physicists themselves were influenced essentially by Machian positivism. For that reason all the philosophical speculation which referred to the "existence" of nature, of matter, of space, of time or of force was eliminated. Clarity could be attained and hopeless complications and contradictions be removed only through the very determined and disrespectful (one might almost say brutal) insistence on the principle that a scientific declaration possesses true content and sense only in so far as it expresses relations and regularities in the material of our experimental experience. The development of this principle requires careful analysis of all propositions. We saw that the proposition that two certain events occurred on the earth and on Sirius simultaneously required penetrating analysis, the results of which finally led us to new, unexpected conclusions. It often happens that just such propositions which we are wont from long habit to use without further analysis are actually shown to require analysis on the basis of positivist criticism. We saw, in relativity and in quantum theory, how our most habitual forms of

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representation and methods of judging had to be revised.

Basically every proposition can be subjected to penetrating analysis. For each assertion, as we usually state it, can be reduced or resolved into other assertions which are more directly dependent upon experimental determinations and events. Here there is no final limit of analysis. (This point was not estimated quite clearly and correctly by Mach.) For just this reason analysis and criticism on the basis of epistemology can and need not work in a vacuum; it must not accept just any proposition and argument (it would lose itself in the endless thereby), but it must by its analysis and explanation establish the domain where the actual and fruitful problems of scientific research lie. It is the task of the instinct of the successful scientific worker to find the places where perceptive criticism is necessary and promising; only the practician in research work can guide the considerations of epistemology in fruitful directions.

2. *The Liquidation of Materialism.* The new concepts, resulting from the experiences of quantum physics and their intellectual interpretation, mean a far-reaching liquidation of the classical western world picture developed by natural science from the Greek materialistic philosophy. The opinion has been expressed that the new development is not a "surmounting" but rather a "refinement" of the materialistic world picture. But in a certain measure it is a matter of taste whether one speaks of "surmounting" or "refinement".

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Kant's philosophy also could be considered either as surmounting or refinement of the materialistic world picture according to one's taste; and the revisions introduced into Kant's theories by relativity and quantum theory can be called a refutation as well as a continuation of Kant's conceptions. That depends upon which part of a theory one wishes to consider the essential nucleus and which part as the external part, capable of further development.

The problem is only clarified when it is indicated to what extent the new perception is different from the old one. Actually by comparing the new physics with the materialistic world picture one can determine that today just those theses of the materialistic conception of nature which expressed the conflict between materialistic theories and other ideas are antiquated.

Compared to the lucid and tangible (and because of this clarity so stimulating and fruitful to natural research) representation of materialistic atomic theory, modern atomic physics is essentially more abstract. Our description will already have demonstrated that; but let us once more indicate a few essential features of modern knowledge in which this more abstract nature of modern atomistics emerges. Democritus' atoms were indestructible and invariable; modern "elementary particles" on the other hand are capable of unlimited transformation. Thus a neutron can (in a radioactive "beta-process") be transformed in such a way that three new particles result from it: a proton, an electron and a particle ("neutrino") of a type

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not previously mentioned, that assumes, as it were, a position intermediate between electron and light quantum. The proton, in turn, can likewise be resolved into three particles; namely, a neutron, a "positive electron" (that also exists), and again a neutrino. Positive and negative electrons can mutually "compensate" for each other in such a way that there remain only one or two excess light quanta; conversely, negative and positive electrons can again be produced in pairs out of light quanta. Analogous processes certainly exist for the proton, although they have not yet been observed experimentally. Light quanta can disappear completely through absorption in atoms, or conversely, can be produced anew.

In Democritus' representation each individual atom had a definite destiny and possessed in its indestructibility and invariability the permanent guarantee of its lasting identity; while the electrons and other elementary particles of the modern physicist, aside from their destruction and conversion properties, possess no individuality. The meaning of this determination has been amply explained above.

Finally, the existence of atoms is no longer a primary basic fact of nature; it is only a special part of a much more general and comprehensive phenomenon—the phenomenon of quantum discontinuities. Whereas we dwelt at first on the historical development of the atomic concept and then recognized quantum effects as phenomena associated with these atoms, the logical and modern interpretation is just the reverse. The basic

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fact is the presence of something which absolutely defies verbal expression and clear representation and can only be approximately indicated by the term "discontinuity". This elementary discontinuity, characterised by the Planck quantum of action and amenable to a complete, quantitative comprehension in mathematical formulae, is revealed among others in the somewhat clear fact of atomistics. We became familiar with the dualism of waves and corpuscles; we know that under certain circumstances nature is revealed in a form corresponding to the simple atom representation; but we also know that it can be revealed from other angles and that then the elementary discontinuities appear in other forms.

The atom, or electron, as we know it today, is therefore completely different from Democritus' atoms; and again it could be designated as a question of taste whether atomic physics in its modern state is to be regarded as a "refined" confirmation or as a radical refutation of the ideas physicists of the last century entertained about atoms. Democritus had declared all the "qualities" of color, of smell and taste or heat an illusion and ascribed to atoms as true properties only those of bodily form and motion. But Mach had already spoken out against the prevailing physical ideas in his positivist criticism. The assumption that qualities had to be ascribed to atoms as we perceive them with the sense of sight and the sense of touch is precisely as arbitrary and superfluous as would be the assumption that the qualities of color or musical pitch had to be ascribed to them. The new de-

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velopment added justification to Mach's criticism and raised the importance of the geometrical properties against other qualities. The atom, as we know it today, no longer possesses the tangibly-clear properties of Democritus' atom but it is stripped of all sensual qualities and can only be characterised by a system of mathematical formulae.

The unbridgeable conflict of materialistic philosophy and positivist theory of knowledge is especially sharply prominent on this point. For with this determination one of the most prominent features of the materialistic world picture is conclusively liquidated; at the same time the positivist theory of knowledge is confirmed and decisively verified.

People today frequently advance Ernst Mach's challenge to the atomistics of that time as disproven by later experiments; and Mach's estimation, unsuccessful as stated, of the most significant problem of physical knowledge is often introduced as a basis of proof against positivist perception criticism in general. But these arguments are obviously based on a completely obsolete and antiquated conception of "microphysics"; the proposition that our experiments had confirmed the reality of atoms could—in this rough form—only temporarily, in the first quarter of this century, be considered correct. For the information described in Chapter Two, which first appeared to confirm the basic idea of Democritus, stands in contrast to the quantum phenomena, treated in Chapter Three, which forced us finally to a very different evalua-

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ation of the total condition. From a really modern standpoint the older idea of the atom must be regarded as just as much disproven as confirmed, since the corpuscular concept considers only one side of the picture, neglecting the other complementary side. If the quantum theory strips the atom of its clear tangible qualities and leaves only a framework of mathematical formulae for its characterization, our theory of knowledge attitude is confirmed again—physical research aims not to disclose a “real existence” of things from “behind” the appearance world, but rather to develop thought systems for the control of the appearance world. The atom, characterized only as a framework of formulae, is, similar to the earth’s geographical degree net, after all only a framework for the classification of experimental facts.

Of equal importance philosophically is the surmounting, brought about by the new physics, of “fatalism”, which had reached complete development in classical physics. In the last century it was imagined that the motions of atoms were regulated by laws similar to those controlling motions in the planetary system—so that all nature in each very fine detail is like a ticking clock, whose run from the very first to the most recent times is predetermined with absolute mathematical strictness. This method of representation was depicted by DuBois-Reymond with fascinating clarity. Imagine a thinking spirit that is infinitely superior to us in quantitative capacity, but qualitatively possesses the same thinking ability as we. He has the abilities of a “complete” mathematician; i.e., he is able

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to complete calculations in a fraction of a second which would occupy all the mathematicians of the world for a thousand years. Besides, through experiment and observation he knows the condition of the world in every detail at a definite point in time; he knows where each atom was at that time and how great its velocity was. Then this "Laplace spirit" would know everything which human savants could ever know. For him all future events are completely calculable in advance. Likewise he can see back into the past; his calculations advise him of every unexplained crime and every lost secret action. Every human cerebral fibre, past and future, is known to him precisely and he can calculate every human action.

The new physics declared the thus illustrated scientific world picture as plainly erroneous. We know now that there can actually be no question of pre-calculable determining causality of all atomic processes. Though this causality and ability to calculate really exists in the planetary system, in microphysics of atoms and quanta something new and unpredictable may happen at any time.

This determination deserves special attention in regard to living organisms. It was impossible for the manner of representation explained by DuBois-Reymond to imagine that the strict causal pre-determination of all atomic motions should suffer an exception in the human brain; in logical consequence man had to be explained as a complicated, mechanical automaton. The strong opposition of this thesis, "l'homme machine" to the religious world was elaborated with especial joy by the bel-

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ligerent representatives of materialism.

By now we know that we can only refer to an exact, predetermining causality in the realm of macrophysics; we must consider whether living organisms are also to be added to "macrophysics" in this sense. Every living organism, even the smallest, is indeed a powerfully large structure in comparison with an atom; but that is not sufficient reason for designating it as a "macrophyhsical" structure. For the characteristic of an inorganic-macrophysical body is that at times it contains innumerable atoms which are of the same sort and are subject to the same external conditions; here, and here only, can complete causality over the destiny of the macrophysical body be assumed as a result of the statistical laws to which its individual atoms are subject. In the living body the state of affairs is entirely different; for all parts of the living body exhibit wonderfully fine and most highly complex developed structures. The discovery of the microscope made the fulness of these complicated structures accessible to us; but they continue down below the limits of microscopic visibility, certainly in part down to "colloidal" and molecular dimensions. Correspondingly, the quantities of matter which take part in certain very fine, but decisively important physiological reactions apparently often embrace only a few molecules.

Most primitive physiological experiences teach us that reactions involving large exchanges of energy and chemical substance are controlled by other processes which are much finer. Consider that in the higher animals (vertebrates, arthropoda)

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the "macrophysical" muscular motions are controlled by the nervous system, by much finer processes which occur in the brain and other nerve centers. The supposition appears justified that similar relations occur in many forms in organic life; and there is basis for the conjecture that the "final" controlling relations are of absolutely atomic-physical fineness. Thus one knows, e.g., that the light sensitivity of the eye extends down to a few individual light quanta. And heredity research, which shows that individual organisms are composed mosaically of their hereditary factors, raised to the surface as a quite general regularity an elementary discontinuity in the variation of the heredity factors. Obviously here we are also approaching the atomic and quantum physical discontinuities of elementary events.

If the supposition is correct that the controlling reactions of organisms are of atomic physical fineness, it is evident according to our modern knowledge that the organism is quite different from a machine and that its living reactions possess an element of fundamental incalculability and unpredictability. One can object that our fundamental understanding of life phenomena is not greatly aided by considering a statistically functioning dice cup instead of a machine as the pattern of the organism. But at the moment it is only important for us to determine in the negative sense that the machine theory of organisms (including their further results; e.g., in the sense of a denial of the freedom of the will) can hardly exist in view of the new physics. Bohr, who vigorously expressed

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his conviction of the fundamental importance of the new physics for the problems of biology, saw a difference between quantum physics and biology in that in quantum physics we study the statistical behavior of individual atoms under well defined conditions, while the internal conditions in living organisms may no longer be definable in atomic measure—so that here still closer limits are imposed on observation than in atomic physics. The new concept of complementarity, which resulted from quantum physics as a new scientific thought form, must according to Bohr be of fundamental importance for the investigation of life processes independently of all knowledge of atomic physics. It is a fact, familiar to every man, that all attempts to investigate more precisely the inner conditions of a living organism are narrowly limited if one wants to avoid (completely or partially) killing it. These limits will gradually be extended considerably by the discovery of better observation instruments. But it is obvious to suppose that limits will exist for that—that here also a fundamental complementarity relation exists, which appears to be a characteristic of the living. In atomic physics we learned to interpret the process of observation as a powerfully active interference on the observed object; in the living organism this undissolvable combination of determining observation and disturbing interference is shown most strikingly.

These indications suffice to show what a wonderful perspective the new physics opened up for biological research. The idea of complementarity, developed in atomic physics to a conclusive idea

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structure, made it possible to reconcile the confidence of our hope in a deeply penetrating natural scientific comprehension of life processes with the conviction that the characteristic of the living lies in its ability to deprive itself of the defining objectivization of its internal conditions.

3. *Positivism and Religion.* For centuries the natural sciences supplied the sharpest weapons to anti-religious movements. Since the anti-religious movements in Europe today seem to have passed their high point and are beginning to be dissolved due to opposing currents, it is a pressing demand of the time to recheck the relation of the natural sciences to religion and to determine whether the anti-religious belligerent attitude of the natural sciences, culminating in Haeckel's time, is still possible today.

A test of these questions will have to examine the noteworthy ideas which Bavink explained in his "Contributions and Problems of the Natural Sciences",¹ and which were more definitely represented in a smaller book to which he gave the characteristic title, "Natural Science on the Way to Religion".² The great success of these publications shows that Bavink's thought processes coincide essentially with the desires and needs of the present time; and I wish to state that this readiness to accept his ideas, according to my conviction, need not correspond to a temporary fashion trend. Bavink developed the concept that, in opposition to earlier, materialistic science, modern

¹ Fifth edition, Leipzig, 1933.

² Second edition, Frankfurt a. M., 1933.

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development of science is pressing toward a re-erection of the religious world picture.

Bavink's conclusions about the liquidation of the materialistic picture of nature are doubtless essentially correct. But we do not want to overlook the importance of a very careful proof of the problem in accord with the religious importance of this determination. The difficulty of the problem results from the fact that the religious world picture itself is not conceived as fixed in all its details but as progressively developing and changing. Consequently it isn't at all certain which scientific theories "contradict" religion. For example, consider that before Copernicus and Columbus hell was beneath the earth and the kingdom of heaven was above the stars. The knowledge that the earth is a sphere and Copernicus' theory of its motion thru interstellar space strongly opposed the former ideas. A retrospective, cultural, historical consideration leaves one hardly any doubt that the reversal on this point has taken part of its vitality and persuasive power from religious doctrine by forcing a more abstract formulation of its conceptions. Despite these, no one today, any more than at that time will consider these natural scientific theories as a contradiction to the religious concept world. The various possible religious evaluations of natural scientific or philosophical theories are also shown in the example of Kant's philosophy. It stands in very sharp opposition to previous philosophical systems which rested more closely on theological concepts and tried to support and confirm these in meta-

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physical constructions. Kant declared the "mechanistic" world picture (i.e., the idea and representation world of materialistic philosophy in the precise form obtained through Newtonian mechanics) to be the only possible basis for natural science. Thus he severed all possibilities for a knowledge of God based on a metaphysical interpretation of nature. Bavink properly underscored Kant's close positive connection with the materialistic or "mechanistic" natural philosophy—a relation often lacking sufficient emphasis. In his important work on the "History of Materialism" Friedrich Albert Lange presented Kant's philosophy dually as a "refinement" and as a "surmounting" of the materialistic world picture.

Kant himself testified to the deep impression made on him by the study of Newton's works, advancing the so-called "Nebular Hypothesis" of the origin of the planetary system. He taught—admittedly in a hypothetical construction—that not only present planetary motions result from Newton's laws with complete causal certainty, but the origin of the planetary system from an original chaos of nebular matter was also to be imagined as a scientifically understandable process on the basis of Newtonian gravitational attraction. Therefore Kant extended and progressively intensified the representation of the planetary system as a clock ticking according to law, requiring no regulatory supervision by the world creator so that the origin of the planetary system is also to be understood according to natural law without the intervention of the creator. "Nous n'avons pas

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besoin de cette hypothèse", declared Laplace.

But while on the one hand Kant explained that a mechanical consideration of nature was the only possible form of scientific thought, on the other he made the materialistic philosophy "innocuous" by severing from it its metaphysical conclusions (in the anti-religious sense) by a very shrewd, grand thought process. He declared, namely, that the mechanical world picture of natural science was necessitated simply by the invariable thought forms belonging to the human mind; our interpretation, the mechanical world picture, is not dependent upon nature itself; the compulsion for this idea results from the internal design of our mind. Consequently the character of nature is not expressed at all in the basic theses of the mechanical explanation of nature, and the usual evaluation of these basic theses in metaphysical conclusions in the sense of the materialistic anti-religious philosophy is impossible.

That Kant, in carrying through this development, actually unjustifiably made the basic conception of Newtonian mechanics absolute could only be clearly recognized later, after the creation of relativity and quantum theory. Until then the problem of science and religion could have been viewed as satisfactorily solved since by recognizing unlimitedly the mechanical world picture as a thought form of natural science, religious metaphysical concepts had attained a position for natural scientific thinking and conclusions which was absolutely not assailable. From the standpoint of Kantian ideas it could be declared that there was no occasion for

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religious thinking to consider it desirable or significant to replace the mechanical picture of nature by another one.

But actually historical development proceeded so that Kant's philosophy could not prevent materialism in any way from radically completing its own anti-religious metaphysics. Haeckel and his allies simply did not recognize the position Kant had given to religion and drove the battle for unlimited materialism further with philosophically gross but propagandistically effective thoughts and catch-words. Actual historical development forces us to the conclusion that Kant's surmounting of materialism in its very abstract character could not permanently obstruct the anti-religious movement. This consideration must induce us to agree unconditionally with Bavink in his idea that the modern liquidation of the materialistic, mechanistic picture of nature signifies a positive gain in freedom of motion for religious thinking.

An important distinction between Bavink's ideas and the theories of modern physics is yet to be established insofar as Bavink spoke out temperamentally and definitely against the positivist conception of the character of physical knowledge; positivism is unacceptable to Bavink. Or rather, let us say that until now it has appeared unacceptable to him, for Bavink, who shows a ready disposition towards new natural scientific developments has openly revised many details of his ideas; thus, it is perhaps not out of the question that his opposition to positivism might yet be changed in the future to a closer connection with the general

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convictions of modern quantum physicists.

For—and this should again be underlined—positivism is not a private affair. Naturally it is not dependent on the word “positivism”. Every active investigator will claim the individual right to assume his own position in the finer shadings of epistemological methods of interpretation. But there is an epistemological conception, basically absolutely uniform, among modern quantum physicists and one cannot reject this conception of modern physics without also rejecting quantum mechanics itself—or in any case regarding it as still unfinished and unexplained. The necessity of this conclusion is also absolutely recognized by the above mentioned physicists (Planck, v. Laue, also Einstein) who reject “positivism” and consequently do not recognize modern quantum physics as conclusive but hope for a restoration of the “mechanical”, strictly causal picture of the world. Bavink, who for his part welcomes the surmounting of the mechanical world picture, through his rejection of positivism turns against the new physics which effected it. We must regard them as inseparably connected; the new physics is not conceivable without the influence of the positivist perception theory; conversely, positivism was first stabilized and rendered precise with the replacement of thinking in objective processes by the new thought form of complementarity.

The endeavor to escape positivism is essential for the manner in which Bavink chose to find in modern science a confirmation of religious doctrines; he wanted to find a direct road to a posi-

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tive recognition of God through the penetration of the secrets of nature. This approach is closed for the positivist attitude because positivism fundamentally disputes the possibility of collecting, classifying and describing observation facts themselves with our knowledge. Positivism denies every possibility of a natural "character perception". The radical rejection of the materialistic philosophy to which positivism leads is a result of just that positivist criticism which denies to materialism the characteristic assertion that the "character" of all things has been found in matter.

Thus in this direction we cannot follow Bavinck. But not only is the resultant liquidation of materialism an important enough result, but also the positivist conception offers new possibilities of granting living space to religion without contradiction from scientific thought. Let us remember that positivism accepts experimental observations and experiences as the sole "reality" for the physicist. The emphasis on this concept leads us to the fact that there are experiences possible which are quite different from those observations and results classified in the physicist's system. As long as the objectivity of all physical phenomena appeared unopposed and self-evident one could try to ascribe to the products of this objectivization, to the objective physical events in time and space, a sort of "higher" reality than to the direct observation experiences themselves. But after we have just learned differently here, we are no longer forced to place physical experiences in opposition to the small fraction of all human experiences

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which depend on the measuring instruments of the physical laboratory or observatory. Let us return to the problems we considered when we said that the physicist represents blue light by a wave motion of a definite wave length (or today also by a stream of quanta of definite energy). At that time we already warned against the manner of expression which was common in the pre-positivist times of natural science—the assurance that now the “character” of blue color is recognized and the direct sensation of blue in Democritus’ sense is unmasked as pure opinion. The logical execution of the positivist conception must establish that “blue” as such is simply an accepted expression; but there are further possibilities of inducing various other phenomena out of the blue light by using certain refined apparatus; and these phenomena are of such great interest to the physicist because there are various properties to measure in them. These phenomena to be expected from the use of the apparatus in question can be qualitatively predicted with all the details of the measurements to be performed on them by the wave theory, or, if quantum physics experiments are to be performed, by the complete, dualistic quantum theory of light.

This reformulation, necessitated by positivism, of equal importance among the different possible experiences, may in its further analysis become very essential to the clarification of the problem of the mutual relations of scientific knowledge and religion. We want to emphasize a few points which may have definite importance

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in this connection. First, let us remember that in the above philosophy we already introduced a distinction between a philosophy which tries to make scientific assertions and one—we designated it as “wisdom”—which strives to make no scientific assertions but nevertheless “expresses” something very valuable. Thereupon it was rightly pointed out that a Mozart sonata also “expresses” something which cannot be converted into scientific statements but the value of which is not harmed by this. There do exist things which can be expressed otherwise than scientifically; and the positivist striving for a clarifying cleaning and purging of our scientific system of expression of metaphysical assertions which mistake the limits of the character and capacity of scientific ability to think, places us in so much greater readiness to recognize the importance of other, possible non-scientific expressions in addition to it.

It was impressively shown by the famous psychologist, C. G. Jung, that not only the rational, scientific perception function of our consciousness but also the condition of our subconscious determines our total attitude toward the world. One can so denote the rationalistic free-thinking age, that it fundamentally scorns and disregards the consciousness against the involuntary psychical courses; we know from the modern psychology of the involuntary how much such a procedure must be avenged, since the “displaced” strivings of the involuntary do not lose their force but become condemned to a disturbing and destructive abnor-

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mal function. But against the involuntary psychical courses the non-scientific forms of expression are just as important as the scientific expressions of our conscious thinking.

We have intentionally placed several different considerations loosely beside each other without wanting to enter into a more detailed investigation of their mutual relationships. We do not wish to solve the problem here, but are merely trying to indicate it; the existence and importance of non-scientific forms of expression and spiritual relationships is likely to be of essential importance for the understanding of non-scientific independence of religion.

It is inherent in the character of these forms of expression that we must relinquish the desire to reach religious intelligence from the direct pursuit of natural scientific knowledge. That, however, does not diminish the religious importance of the turning point which occurred in natural scientific thought. For it is only with the positivist liquidation of materialism and limitation of the suitability and significance of scientific thought as well as the positivist limitation of the importance of physical measurements that we gain that balance in the evaluation of our different forms of experience that permits returning their due place to non-scientific experience and expression possibilities.

Such determinations do not comply with the demands of religious theories since religious thought also requires the right of existence for a

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special science—theology.¹ But the tendency, prominent in earlier times and still evident today, of relating the theses of this science to philosophical-metaphysical thought paths is incompatible with positivist criticism. Positivist criticism will only admit to the theses of theological theories a meaningful content when they are shown on closer analysis to be expressions of concrete experiences. This interpretation may be unwelcome on many sides; but it probably contains the indication of a direction which could lead to a conclusion and a new comprehension of lost religious insights much sooner than is attainable from the simple “accepting” of abstract theses. For example, one could consider that the thesis, present in most religions, of the world creator—which interpreted as a quasi-natural scientific expression has undergone a progressive weakening of its content through the development of natural science—possesses a very live meaning in the form of the determination of an unbridgeable difference between the “created” nature and the technique discovered and “made” by the people. This is a theme of vital importance to us children of a technical world; and there are voices present today which see a specific religious problem in our relation to the technology.

But here we have reached the point where the author, who speaks here only in his proper position as a physicist, must resist the temptation to spin further the threads of the thought begun

¹ “Theology” here means any striving for systematic religious thought development without limitation to Christian theory. Thus, in this sense, each developed religion possesses its theology.

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on his own justification. To many a reader it may possibly seem disappointing that we should halt right now in our wandering and should leave the final and most moving problems hanging in suspense. But if it is characteristic for philosophers not to want to rest without having found the conclusive solutions to all problems in a separate "system", there belongs to the natural scientist another attitude which Newton expressed as follows: "I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

Thus let us be happy to see that the thoughts have come in the stream and that the gates of new developments are open. The attainment of new natural scientific methods of representation of complementarity means the maturity and conclusion of an epoch of the richest gains for the understanding of atomic and quantum physics. But the evaluation of the new thought processes outside of physics in the problem of biology and the thinking through of philosophical and religious questions still stand at the real beginning; their results are not to be disregarded. Let us be happy that our ship has weighed anchor—for a journey to new shores.

APPENDIX

I. COSMIC RADIATION

In 1912 V. F. Hess in a balloon ascension discovered a remarkable radiation which falls onto the earth from outer space. Numerous further investigations have since been devoted to this phenomenon. The first steps of the further investigation were only slowly obtained; around 1924 the reality of the phenomenon was still absolutely doubted by outstanding physicists. For the problem involves a radiation which not only remains invisible to the eye but is also inaccessible to the perception of all rougher physical instruments; only the extremely refined research methods developed for the investigation of radioactivity—the Wilson cloud chamber and the counting tube—permitted the proof of the indubitable presence of cosmic radiation and allowed a more precise investigation of its nature.

The further the advance in these investigations, the greater became the number of unsolved problems presented by this radiation; but the greater became also the stimulation to pursue this peculiar phenomenon. In recent years cosmic radiation has become one of the increasingly important fields of research in physics. Observations and measurements were gathered on sea voyages and through expressly equipped expeditions from Spitzbergen to New Zealand and Tierra del Fuego over all the oceans because it appeared desirable to determine the strength of incident cosmic radiation over the

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entire surface of the earth. Measuring instruments were carried up high mountains—e.g., on the Alps and the Peruvian peaks—to see how this radiation behaves up there. Piccard's famous balloon ascents were devoted essentially to the measurement of cosmic radiation at great heights; they were exceeded by far by the recording balloon ascents carried out in Germany and America. In these latter, self-registering measuring instruments were carried in unmanned balloons up to heights of 20 km. and more; they showed that at these great heights the intensity of this atmosphere radiation, not yet weakened by passage through the earth's atmosphere, is about 200 times greater than at sea level. In other investigations the measuring instruments were submerged in deep lakes for hundreds of meters; there they measured the smallest traces of radiation which penetrate down to these depths and which belong to an especially penetrating portion of this radiation. Still other investigators descended into mines for observations on atmosphere radiation.

A main goal of these investigations was to gain information about the origin of cosmic radiation. It is certain that it approaches the earth from outer space; but we know almost nothing positive beyond that. It definitely does not come from the sun; and the conjecture, entertained for a long time, that it somehow came out of the milky way also had to be abandoned. For then the motion of the milky way over us (as it results from the rotation of the earth) must cause periodic changes in the strength of the atmos-

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phere radiation to be recognizable; and experiments show reliably that such is not the case. So they had to resolve to assume the origin of cosmic radiation in the depths of world space far beyond the milky way. There have been attempts to combine definite occurrences in stellar development with the production of this radiation; but these are still of a very hypothetical and uncertain nature. Meanwhile we must be satisfied with exact information from the abundant investigations which were instituted about the arrival of cosmic radiation at the earth's surface and its passage through the atmosphere. The puzzle of its cosmic origins remains unsolved.

The arrival of cosmic radiation on the earth is complicated because the radiation consists of electrically charged particles. These are deflected by the earth's magnetism into complex curved paths which are difficult to follow mathematically. The relations present are similar to those associated with the electrons (coming from the sun) which cause the northern lights. These problems can be designated as extensively clarified.

The penetration of the earth's whole atmosphere which cosmic radiation must accomplish before it reaches the earth's surface would not be possible if it did not possess a penetrating ability that is enormously large in comparison to that of X-rays (and to the radiation of radioactive substances). Thus, lead plates which completely screen off radioactive or X-radiation are almost no hindrance to cosmic rays. This tremendous penetrability is due to the fact that the indivi-

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dual particles of cosmic rays are exceedingly energy-rich. With the most modern technical tools electrical potentials up to a million volts can be produced; with these potentials very high velocities (thus very high energies) can be imparted to electrically charged particles—protons or alpha-particles, for example. The particles in the radiations of radioactive substances possess energies of similar magnitudes. But the particles of cosmic rays have energies—naturally not equal for all the particles—which extend to over a million times this magnitude!

Cosmic rays, thus, give the physicist a unique opportunity, formerly not attainable in any way, to investigate the behavior of particles of enormous energies. The field of research opened up thereby is for the present inexhaustible; we repeatedly discover the most remarkable, most surprising things there.

One of the most beautiful findings was the (p. 146 briefly noted) positive electron ("positron"). Formerly electrons were known only as negatively charged particles; positive charges appeared to be found only in atomic nuclei. In cosmic rays approximately as many positive electrons were discovered as (fast) negative ones.

These positive electrons do not appear on the earth as permanent constituents of matter because they can be mutually annulled by negative ones. In the closest combination of positive and negative electrons their charges neutralize one another since they are opposite and both particles disappear—leaving only an indestructible quantity

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of energy, possibly appearing as a light quantum (or in another form of energy). Conversely, the production of a positive and a negative electron can occur from collision between energy-rich particles or by the close passage of an energy-rich light quantum and an atomic nucleus. Such processes occur over and over in the atmosphere which cosmic rays traverse.

The energy-rich particles which can progressively tear off electrons from the air molecules they pass can therefore cause ionization; occasionally they also impart a large amount of energy to one of the loosened electrons. But mainly the rapidly moving electrons expend very large amounts of energy in the form of very energy-rich light quanta by rushing closely by atomic nuclei; these quanta in turn produce more electron pairs.

Collectively these relations become very complicated and it is understandable that a complete disentangling of the state of affairs has not yet been successful. It is not quite clear what type the primary particles of cosmic rays really are; almost all of the particles present therein are indeed only secondary, or tertiary, or . . . etc., produced by successive processes.

Under certain conditions—e.g., if we pass the cosmic rays through a lead plate several millimeters thick—this production of electrons (positive and negative) from energy can occur to such an extent that a whole shower of newly produced particles—several hundred or even a thousand of them—spray out from the same, or almost the same, point of production in the lead plate. This

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remarkable phenomenon has already become the subject of much careful research. The progressive theoretical treatment of the data gathered thereby will yield important insights into the most profound, unopened natural laws of matter; in a certain sense these are nowhere as clearly and characteristically expressed as they are for very energy-rich particles.

Even before their experimental discovery (Anderson, Kunze) the existence of positrons was predicted on the basis of the profound theoretical considerations of the Englishman, Dirac; a theoretical prediction, which, when it was made, appeared so bold that most physicists refused to believe it at the time.

Since then, these processes of the destruction and production of electrons—thus material particles—have been experimentally checked and investigated in all directions. Fundamentally they show clearly that the elementary particles of matter, the proof of the existence of which meant such a wonderful triumph of Democritus' ideas, in the final analysis are quite different from Democritus' atoms. The simplest, final elementary particles of matter are not at all, as Democritus dreamed, impossible to create and indestructible elements of all events. If they are really incapable of any internal change in condition they can still both appear and disappear. To be sure this has only been shown above for the lightest material particle, the electron; it is also valid for the heavier material particles, as is briefly intimated at the conclusion of these considerations.

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We have mentioned (p. 82) a recently discovered, previously unknown elementary particle, the so-called "neutron" (Chadwick). It is very similar to a proton, especially since it has almost the same mass; but it has no electrical charge and is neutral. The great German physicist, Heisenberg, had made it clear that all atomic nuclei are built up of protons and neutrons. But our already tremendously extensive experience with nuclear transformation processes (element transmutations) shows a proton can be changed into a neutron, and conversely a neutron into a proton. The transformations proceed spontaneously in radioactive substances without our aid; they can be produced in many other nuclei by "bombardment" with very energy-rich particles. Each time this transformation takes place, besides, an electron (positive or negative) is produced anew, and also a "neutrino", a particle of still little-known nature. Possibly such particles also play an important part in cosmic radiation.

If we add to what we learned about the fundamental dualism of waves and corpuscles our knowledge of this ability of material particles to appear and disappear in the most variable manner and not to be absolutely indestructible we recognize that the picture drawn by modern physics is quite different from that to which Democritus and the atomistically trained physicists of the last century were accustomed. Neither atoms nor their building stones, electrons, protons, neutrons, are the invariable permanencies in the change of physical phenomena; they are temporary forms of

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the indestructible we learn to know in physics—energy. The appearance of this energy in the form of corpuscles, material, elementary particles or under other circumstances in the form of its complementary, wave side—is only a specific case of a much more general, much more comprehensive and much deeper regularity; namely, the elementary discontinuity that controls all quantum physical occurrences.

What is concerned in cosmic rays, the puzzle of its cosmic origin, became more mystifying the more clearly it was recognized how energy-rich many of the cosmic radiation particles are. At present it appears impossible to understand by what kind of processes such energies can be imparted to an individual particle. Recently a very astonishing answer to the problem of the origin of cosmic radiation attracted considerable attention; an answer, which of course is purely hypothetical, possibly also incorrect, but which in any case points out a possibility to be considered seriously. According to it, the source and origin of cosmic radiation which rushes through outer space is not to be sought in events that are still taking place in the universe today; it is a remnant of energy-rich radiations, no longer being produced but only gradually being consumed, which were formed in the ancient, original explosion out of which the entire universe arose.

II. THE AGE OF THE WORLD

The discovery of radioactivity shortly before the end of the last century not only furnished the

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physicist with revolutionizing knowledge, it also made new methods and experiments possible for other fields of science.

We explained above (p. 107) the law of decay followed by radium wherever it may be; the same law is valid for other radioactive substances, only the rate of decay differs. This radium disintegration is a process taking place in the nucleus of the radium atom. Whereas usual chemical reactions—as processes which concern only the loosest electrons in the electron shells of the atom in question—can be strongly influenced by temperature and pressure it is impossible to obstruct or accelerate the decay of radium by such means. Rutherford was the first to artificially produce a nuclear transformation (element transmutation); since then physicists of the whole world have been working effectively on the investigation of artificially formed nuclear transformations. But such abnormal means are necessary—bombardment with very energy-rich individual particles—to produce them that one can say that apart from nuclear physics laboratories and occasional effects of cosmic radiation non-spontaneous nuclear transformations never occur on or in the whole earth. We must add that the rapid alpha-particles emitted by radioactive substances occasionally can meet another nucleus and induce in it a transformation—Rutherford's experiment involved just such a process; but that happens so seldom that it is insignificant in our present discussion. Since cosmic radiation can produce effects (which could attract the geologist's attention) only as great as the nuc-

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lear physics laboratories we see that all radioactive substances present in the earth's crust with its different geological strata decay at exactly the same rate as they do in a laboratory; and they not only maintain this rate today, they have kept it all the millions of years the earth has existed. There was also the reliability of being able to subject this conclusion to a direct empirical check by observations on minute radioactive inclusions in rocks which have become faded from the radiation that passed within very close range of each of these inclusions through the course of millions of years; details, that naturally we can not depict and explain more extensively here, permit a check on whether a rate change took place in the course of millions of years or whether perhaps (this was naturally very conceivable) radioactive substances existed in earlier periods of the earth's history that we are not familiar with because they long ago decayed to what are at present imperceptibly small residues. Actually, neither the one nor the other is the case.

If a quantity of radium enclosed in a rock decays at an invariable rate, one can later figure out how much time has elapsed since the radium became enclosed in the stone on the basis of a determination of how far the decay has proceeded. Therefore accurate investigations were performed to determine the extent of the already completed decay on all stones containing radioactive substances within them which could be obtained; from these it was possible to calculate how long ago the stone in question had been formed.

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It is remarkable that somehow such "stone clocks" occur in almost all geological layers; their ticking had proceeded uniformly throughout the millions of years of the earth's history and all its revolutions and permits us late-comers on this earth to read off today the age of the various geological strata.

<i>Geological Time Period</i>	<i>Age in Millions of Years</i>
Neozoic Group	36.9
	58.7
	73.5
Mesozoic Group	146.
	218.
	289.
	360.
Paleozoic Group	430.
	498.
	567.
	635.
Proterozoic	700.
	767.
	831.
	897.
	961.
Precambrian	1026.
	1089.
	1150.
	1212.
	1273.
	1336.
Azoic	1525.

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On the opposite page there appears a summary of the results (from a compilation by O. Halm); for each of the large groups of geological epochs there are several separate values listed for older and younger stone layers.

In general how old is the world? We see from the table that the oldest known geological layers are about one and a half billion years old. The age of the earth is therefore fixed as still greater than this number; but it is improbable that it is much more than triple this value.

It was possible to extend this age determination still further. It can be assumed that the earth was once formed out of the material of the sun; a spiritually rich idea of St. Meyer's shortly afterward showed the possibility of learning something about the age of the sun from terrestrial radioactivity investigations; the result is that a certain period of time, which to be sure does not embrace the entire lifetime of the sun, but a large part of it (perhaps half) can be very exactly specified as 4.6 billion years.

That is a very remarkable result. It might well have been expected that the great sun were a much older inhabitant of the universe than the small earth expelled from it; but as we see, that is not the case at all. No less remarkable are the results of age determinations on meteors which likewise became possible through radioactivity investigations. It was shown that these fragments of the universe which, it is partially demonstrable (through path observations), perhaps do not belong to our solar system to begin with, but are

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hurled at us from further distances of interstellar space, are never essentially older than the sun and earth.

Here we meet problems before which we humbly perceive the limits of our research ability. Physical information is obtainable to a certain degree by executing planned experiments. But meteors from outer space do not appear at our order; here we see scarce material that has been placed at our disposal by the favor of conditions and that increases only slowly. But despite that, who is to hinder us from reflecting over our present findings? And who will dispute that a careful consideration of the findings thus far can be stimulating and fruitful for our further research?

If we summarize our knowledge up to the present, we must say that we have found no body the age of which was shown to be higher than 10,000,-000,000 (10 billion) years. There is no basis for believing that in the gigantic milky way system to which our sun belongs stars are present which are essentially older. And in addition there is no basis for ascribing a higher age than that of the milky way to the "spiral nebulae", analogous to our milky way, which lie far outside of our milky way system in space—the oft described Andromeda nebula is the most familiar example. Is there, therefore, in general anything at all in space which essentially is older than ten billion years?

To approach this problem from a still different point of view; the American astronomer Hubble—stimulated again by certain theoretical consi-

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derations (de Sitter)—with the tremendous instruments which stand at the disposal of American observatories, determined a fact which is very simple to express. Its proof was not as simple as the formulation of the result. An indispensable assumption for its proof was a major achievement of modern astronomers—the determination of the distance of the spiral nebulae similar to our milky way.

With a stereo telescope, the two optic foramen of which lie on two points of the earth's path opposite each other, we can see a part of the stellar sky stereoptically. Instead of the stellar sky perceived by our eyes, in which the stars are little light-points very far apart we would see the planets as spatially very close and many fixed stars as farther away but as yet thoroughly estimable lights with regard to their separation from us. But most of the stars of our galaxy—and all the more naturally the spiral nebulae beyond—will appear to this enormous stereo telescope as immensely distant as to a pair of common human eyes.

Astronomers actually work now with such a stereo telescope; only naturally they must wait a half year between the views (or photographing) through the one and then the other optic foramen—until the earth has carried us from a point on its path to one opposite it. In this way the distances of the closer fixed stars can be determined reliably. But how is it possible to make these determinations on distances which are still quite small for astronomical measure. It must

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suffice here to say that it became possible; ingenious uses of the fact that there are certain "classes" of fixed stars which show (according to observation) simple relations between absolute luminosity and other easily observable properties have made it possible to see still deeper into space than the earthpath-stereotelescope ("parallax determination") reaches. That was only the first step; others followed in a bold structure erected by the astronomers with enormous care and precision. Gradually the entire milky way became extensively "transparent" to us in such a way that we see quite well the spatial division of its stars and star clusters. Meanwhile a final step was executed; distance determinations were made possible for the more distant world islands beyond the milky way system, the spiral nebulae. Here they determined, as mentioned before (p. 32), distances up to 100 million "light years" (and considerably more).

Since there also existed well founded estimates of the total mass of such world islands, it is possible, by calculations on the spiral nebulae met up to a certain distance, to determine by laborious statistics how great the central mass density of the universe is. It is unusually small—in the statistical average only 1×10^{-30} (a one divided by a one with thirty zeros after it) grams per cubic centimeter.

It is very important that this could be determined. Previously we touched quite briefly (p. 50) on certain knowledge concerning which we are spiritual heirs of the German thinker Bern-

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hard Riemann—one of the greatest mathematicians of all time. Riemann had discovered that the laws of Euclidean geometry—which are in no way logical necessities independent of all physical experience—permit a generalization which can be designated as the utilization of the principle of a field of force in geometry. Even before physics had arrived at the field of force principle Riemann had introduced it (without actually using the same name) into geometry. We have already mentioned that these Riemann ideas form the support and mathematical scaffolding for the attempt to grant to the gravitation law also (analogous to the electrodynamic laws) the form of a field of force law. Full utilization of Riemann's ideas leads to the fact that space must not necessarily—as is assumed by Euclidean geometry—be infinitely large. Mathematically spaces having definite finite volumes can be represented without requiring the presence of walls or some other boundaries to close them off. (This can be explained by a simple example which has only one fault, that of being a two dimensional structure, a surface, whereas Riemann's theory refers to three-dimensional space. The surface of a sphere—notice that we actually mean the surface and not the volume of the sphere—has no boundary anywhere, despite which it is only finitely large, i.e., contains a fixed number of square centimeters.)

Knowledge of the gravitation constant¹ and mean mass density of the universe, touched on

¹ This refers to the so-called relativistic gravitation constant, $8\pi f/c^2$ where f is the Newtonian gravitation constant and c is the velocity of light.

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above, makes it possible to calculate the size and total mass of the universe. These calculations were first performed on the basis of more difficult, more complicated theories, the definitive character of which can perhaps be doubted. But if only an approximate orientation, not too exact numerical values, is required it can be shown that the numerical values desired are quite simple to ascertain through considerations which are quite independent of all the still doubtful refinements of gravitation theory. Fantastic as it may seem the (approximate) value of the total mass of the universe, to be considered of finite size, is known $—1 \times 10^{55}$ (a one with 55 zeros after it) grams. The "diameter" of the universe, the greatest separation which can exist between two points A and B in the universe, is also known. (If one goes farther from A in any direction, in every case the separation from B decreases. It is the same as on the earth's surface when a man who has traveled to the south pole always comes closer to the north pole with each step he takes in whatever direction.) This diameter is approximately ten billion light years.

Finally we want to mention the Hubble discovery. If we spectroscopically resolve the light coming to us from a distant spiral nebula we find that it contains spectral lines we know; thus the same laws of atomic physics hold in the farthest reaches of space as here. But these spectral lines exhibit a considerable Doppler effect — we already know (p. 42) what that is—which becomes more pronounced the farther away they are.

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All these distant spiral nebulae are conceived of as in rapid flight; the velocity of which is proportional to the separation of the nebula in question from us.

What does this mean? We have indicated that a very close connection grew up between geometry and physics from the profound Riemann ideas. Now direct support for this relation must be found. Since the flight of distant nebulae is a quite general phenomenon existing not only in single examples but (as far as our knowledge extends) in general in all known nebulae, and, as mentioned, follows a uniform regularity this nebula-flight must be interpreted as an explosion-like growth of world space itself. The universe itself is expanding with furious velocity and thus the separations between the world islands contained within it are increasing proportionately.

The numerical value which is determinative for all flight velocities (velocity of a nebula divided by its distance) is exactly such that one arrives at the determination that the diameter of the universe is increasing directly with the velocity of light. That is not alone and of itself a very rational result which can consolidate essentially our confidence in the correctness of our whole consideration. But it also yields a further result.

Let us look back into the past; the world diameter, growing with the velocity of light, was formerly smaller than it is now; if we mentally pursue the development of the universe farther and farther back, we come to a point where everything is at an end, or rather, everything is at

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the beginning. About ten billion years ago the world diameter, today grown to ten million light years, must have been vanishingly small. So by a very different path we return to the determination empirically arrived at from age determinations; ten billion years ago—Lemaitre especially deserves credit because of the closer execution of this representation—the initially small universe arose from an original explosion. Not only atoms, stars and milky way systems but also space and time were born at that time. Since then the universe has been growing, growing with the furious velocity which we detect in the flight of the spiral nebulae. . . .

It is remarkable that modern natural research gives rise to knowledge and ideas which drive our feelings in such different directions from those of natural research from the times of Lamettrie to Haeckel. It is doubtless very justifiable for the author of a modern book on the mathematical theories of relativity and cosmology to pronounce at the conclusion that our scientific research on the future and past of the universe need not be influenced by human desires and hopes or by theological theories of creation. It is also characteristic that the state of development of our science suddenly makes such warnings necessary again.

But when we pay just recognition to this warning, when we don't allow any motivation for our scientific research other than the inexorable striving after the knowledge of truth, who would hin-

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der us *afterwards* from once dreaming about the results achieved?

And certainly this picture of the universe as exploding fireworks which went off ten billion years ago invites us to consider the remarkable question of Miguel de Unamuno, whether the whole world—and we with it—be not possibly only a dream of God; whether prayer and ritual perhaps be nothing but attempts to make HIM more drowsy, so that HE does not awaken and stop our dreaming.

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